Studies of Higgs physics with the LHC experiments and with quantum computing

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I am an assistant professor in the CMS group at Peking University (starting in Oct 2021)

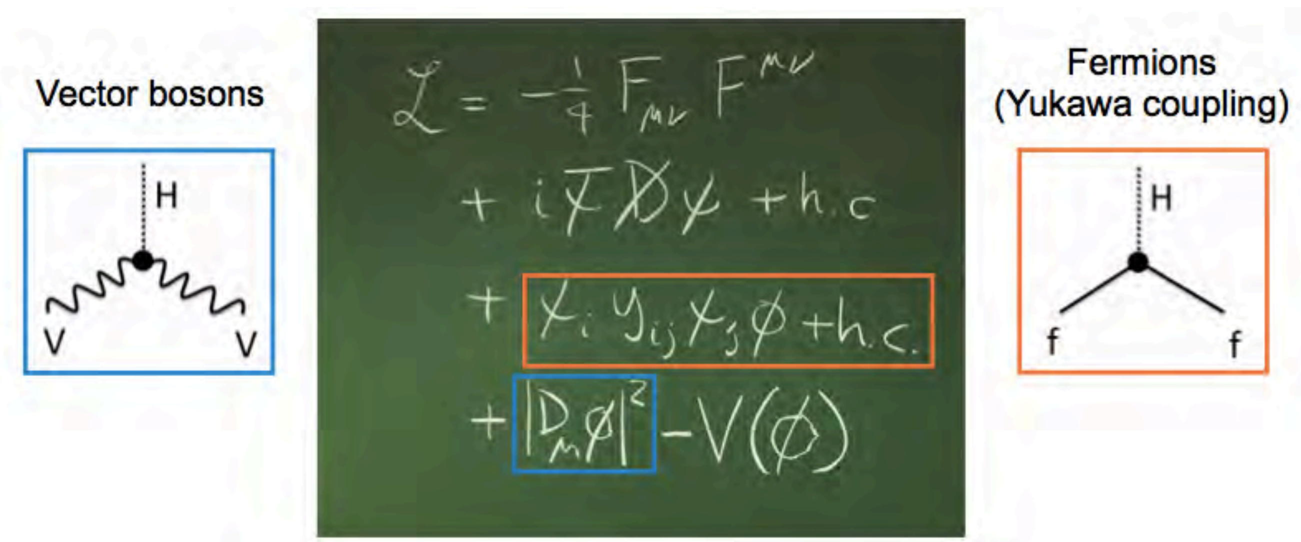
I was working in the ATLAS group at University of Wisconsin from 2016 to Sep 2021

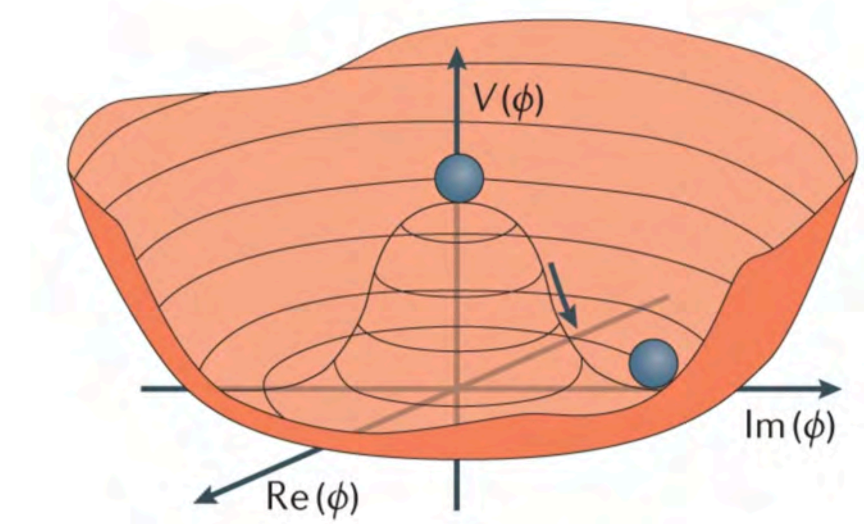
In this seminar, I will mostly discuss results that I contributed to, but also cover other results to make a full story

The Higgs boson

- ***In their famous 1964 papers, Professors Robert Brout, François Englert and Peter Higgs proposed a new, massive boson of spin zero to explain how elementary particles – the building blocks of the Universe – get their masses***

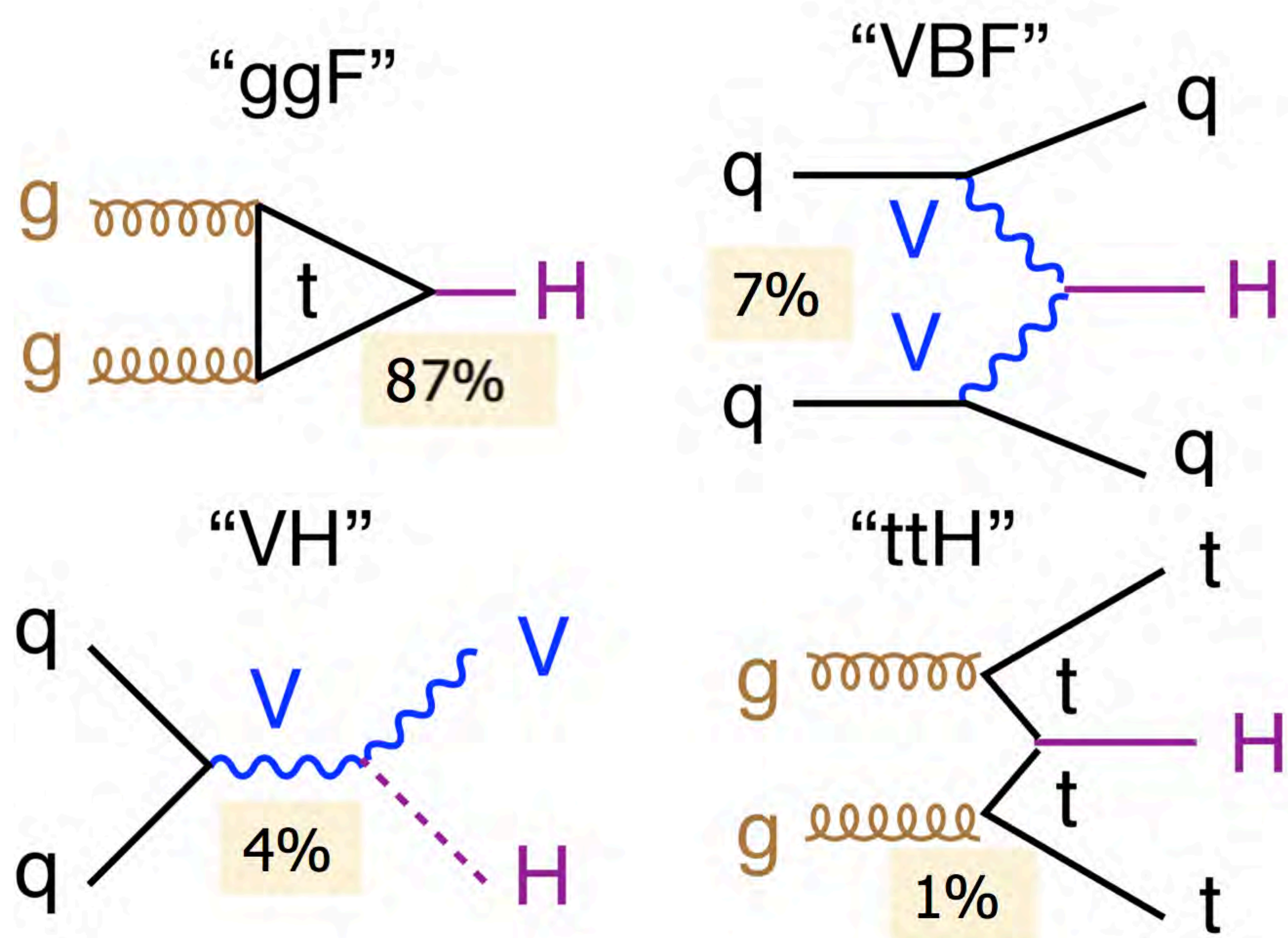
- ***In the universe, there is a Higgs "field" that pervades all of space, turning mass-less particles moving through it into the massive ones***

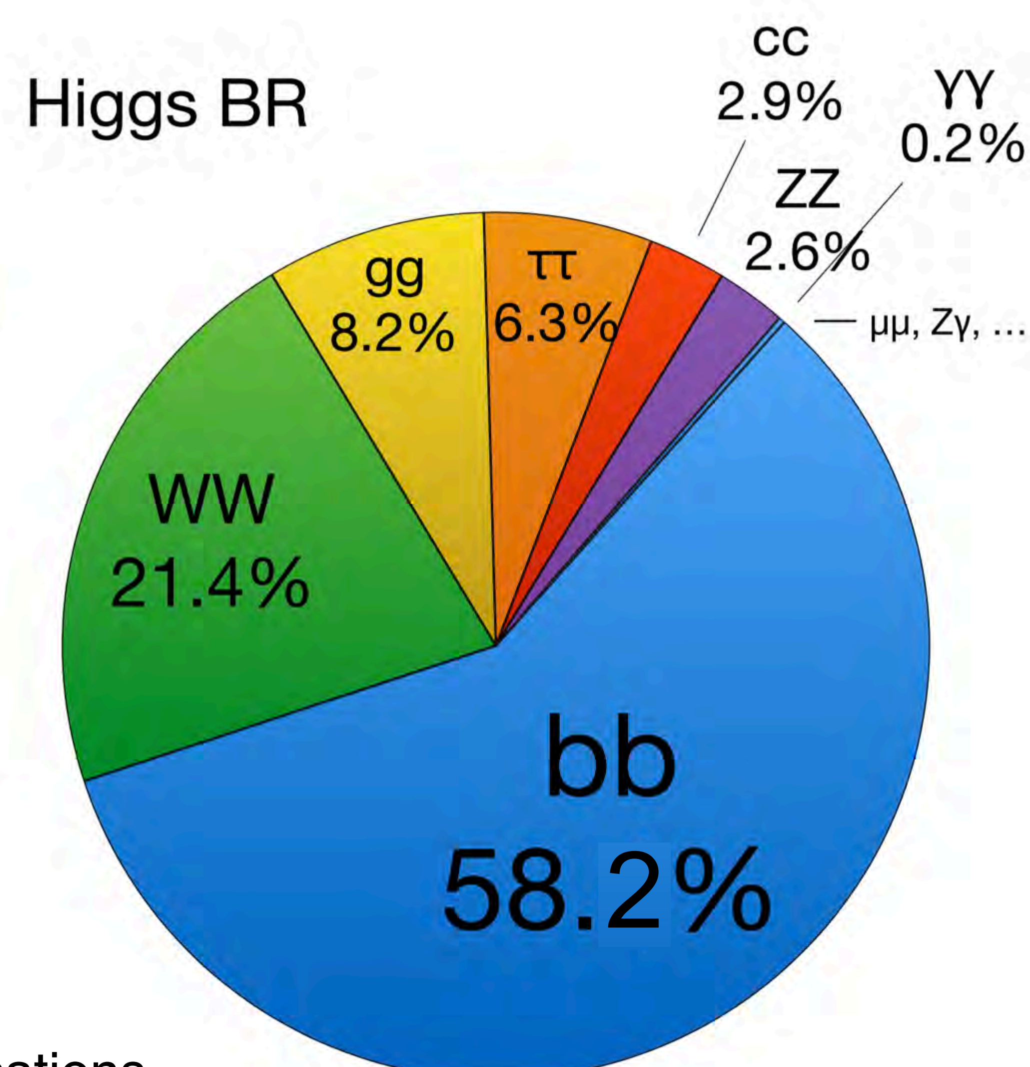




Higgs Boson production and decay modes

- In the Standard Model, the Higgs boson couples to massive bosons and fermions
- These couplings determine the Higgs boson production and decay modes:

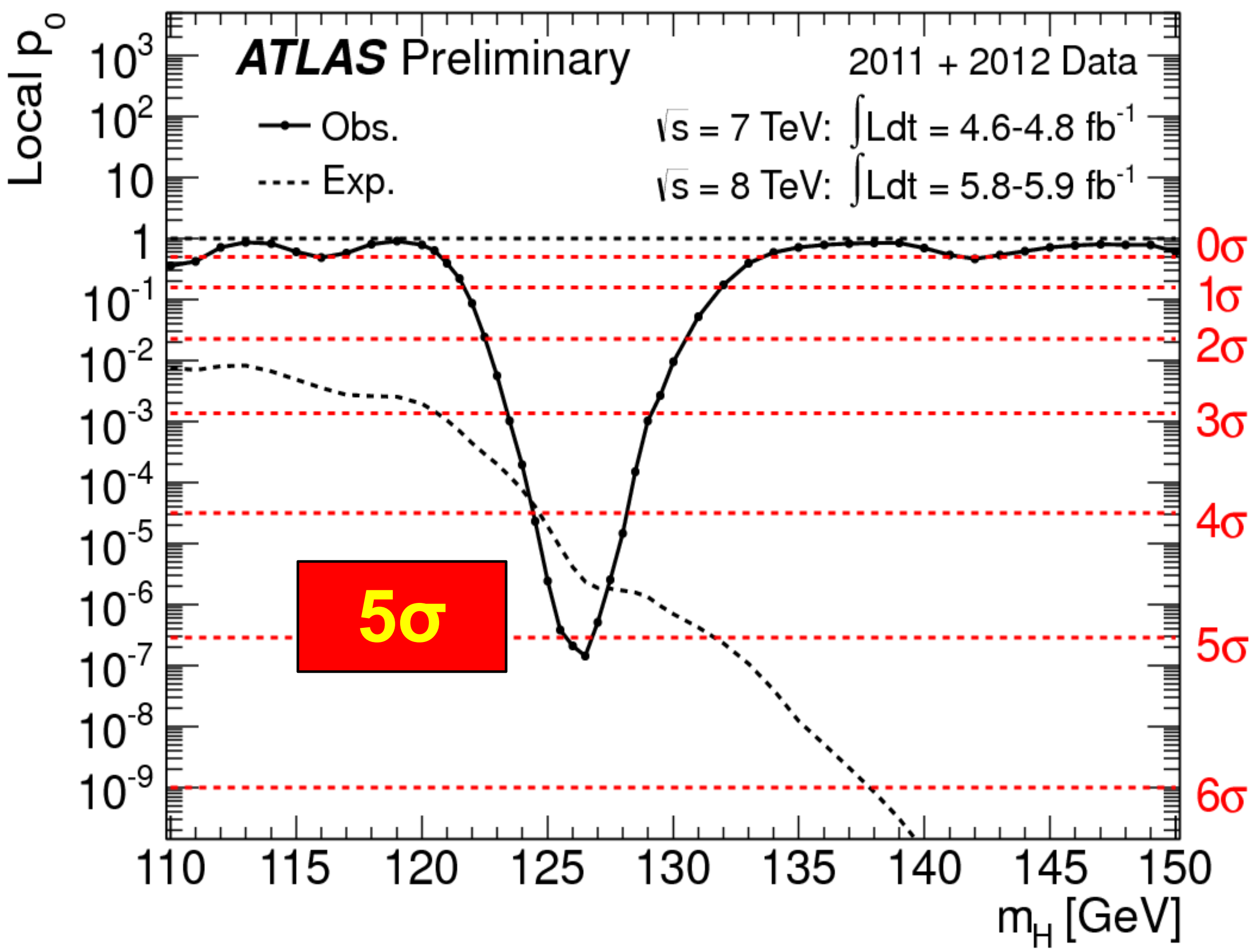




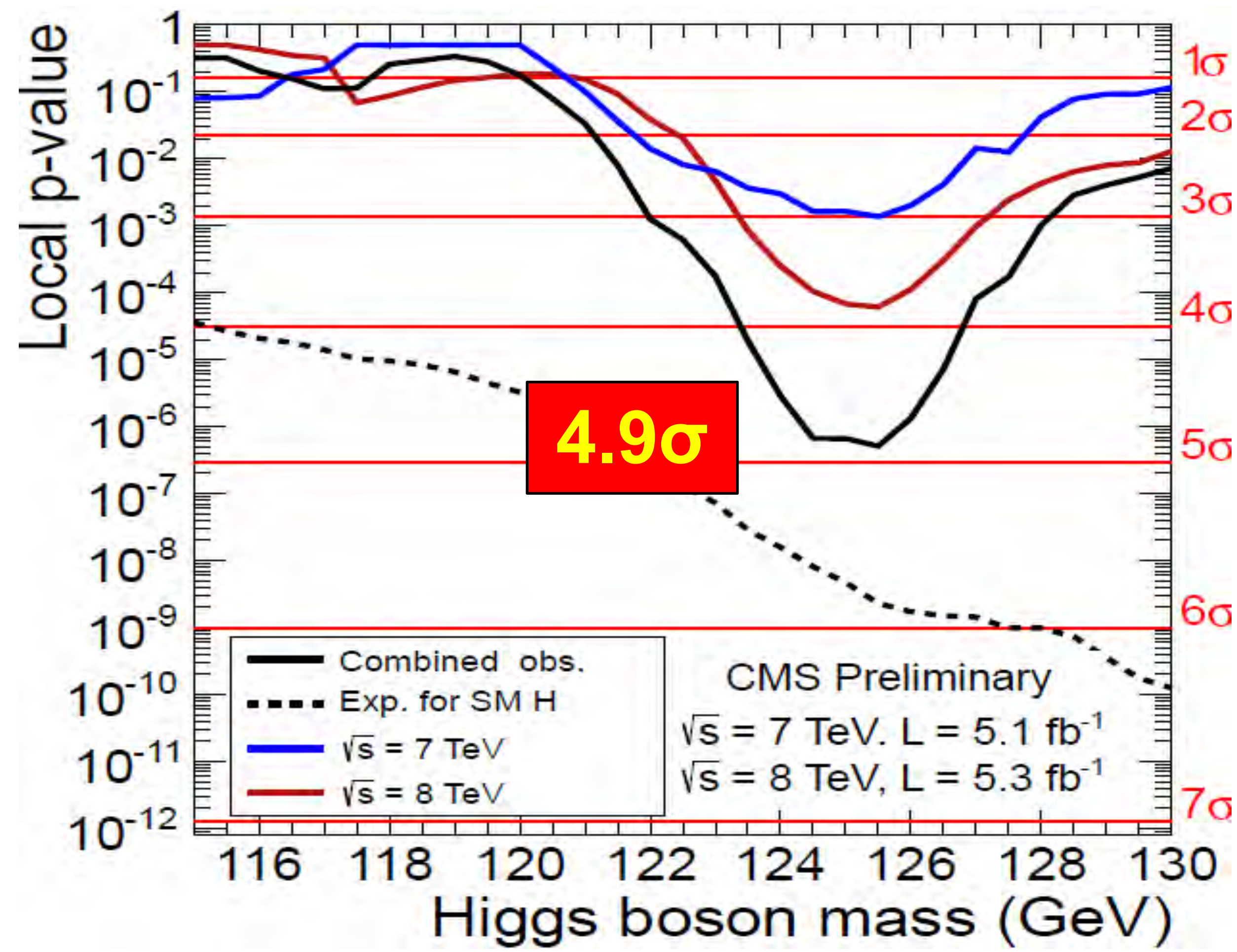
Figures from https://msneubauer.github.io with modifications

The discovery of the Higgs Boson

ATLAS *$\gamma\gamma$, ZZ: 2011 + 2012 data*
WW, $\tau\tau$, bb: 2011 data



CMS *All channels use 2011 + 2012 data*



Largest local excess:
5σ at m_H= 126.5 GeV

With LEE in 110 < m_H < 150 GeV,
global significance: 4.3σ

Largest local excess:
4.9σ around m_H= 125 GeV
(using $H\rightarrow\gamma\gamma$ and $H\rightarrow 4l$: 5.0σ)

With LEE in 110 < m_H < 145 GeV,
global significance: 4.4σ

The discovery of the Higgs Boson

July 4 2012, “Discovery!”

The discovery of the Higgs Boson

- On July 4, at the end of the CERN seminar Prof. Sau Lan Wu went to shake hands with Prof. Peter Higgs. Prof. Wu told Prof. Higgs "I have been looking for you for over 20 years". Prof. Higgs replied "now, you have found me".

Are we done after the discovery?

No!

Studies of Higgs boson properties

- Before the discovery, all known elementary particles had either spin 1 or spin ½.
- The Higgs boson has spin 0, so it is not only a new particle, but a new type of elementary particle
  - For this reason, many see the discovery as the most important step forward in physics in the last half a century
- The Higgs boson's couplings to fermions and to itself are new kinds of fundamental interactions, and have not been fully established
  - Study of these interactions has paramount significance

Studies of Higgs boson properties

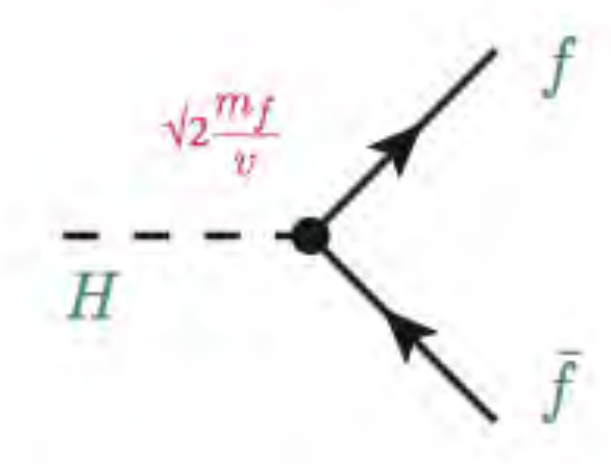
- **The discovery of the Higgs boson** opened a new way to refine our understanding of particle physics.
- **Many studies of Higgs boson properties** have been performed
  - Deviation from the Standard Model (SM) predictions on Higgs boson properties would provide clue for new physics
  - To determine if the standard model Higgs mechanism is really the full extent of the Higgs sector, or if there is new physics with a more complicated Higgs sector lurking nearby
  - Higgs physics research is one of the highest priorities of particle physics

Particle physics is never as exciting as today.

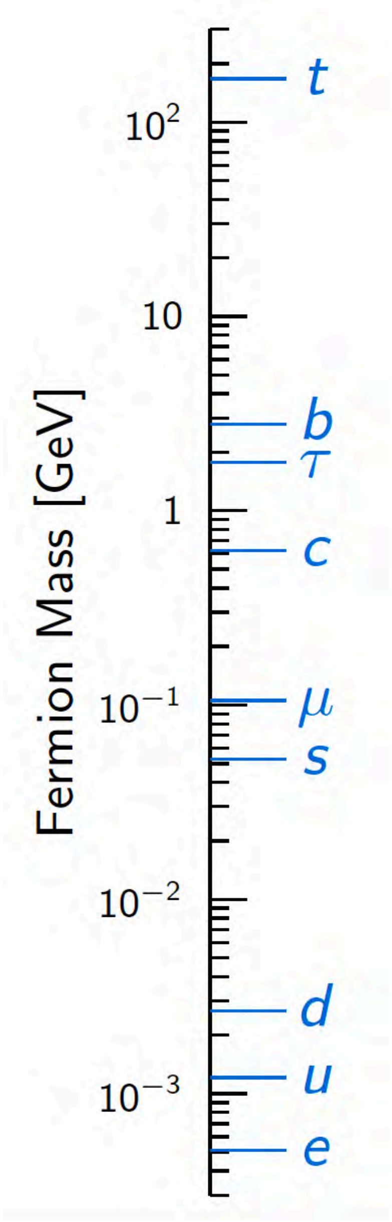
This is largely because of the discovered Higgs boson.

Higgs boson couplings to fermions

Yukawa couplings

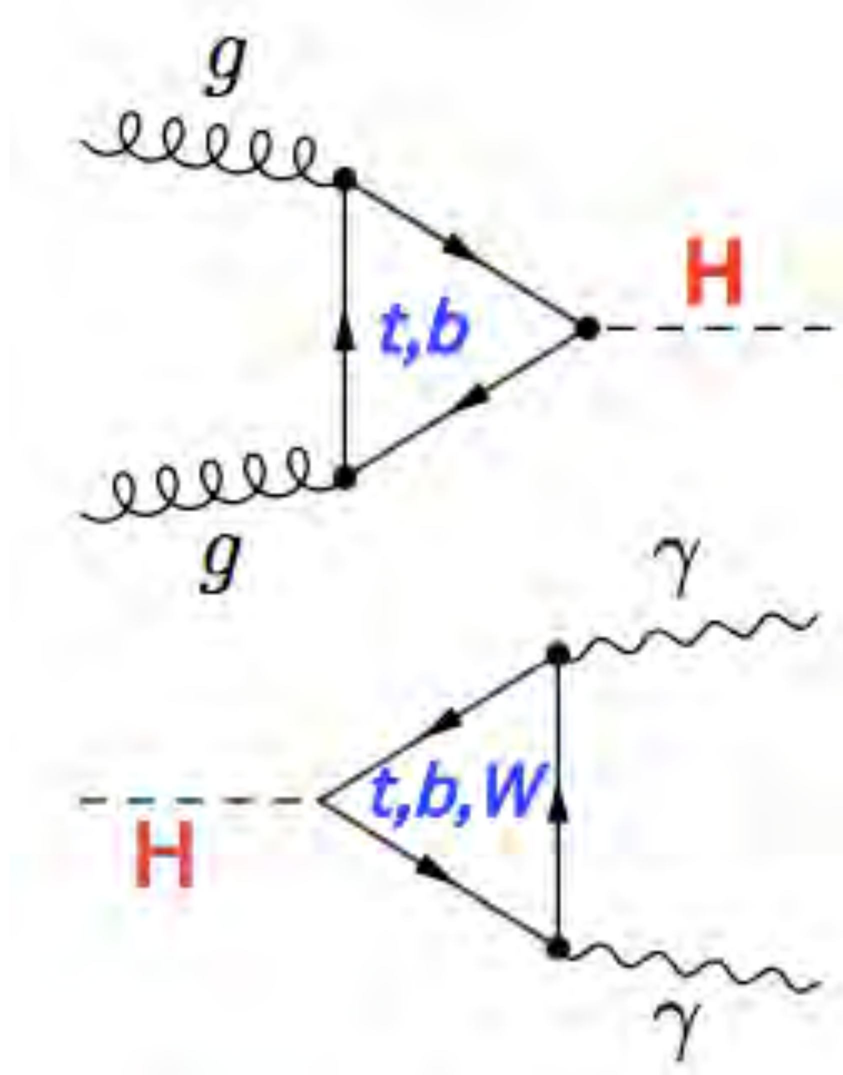


- In Standard Model, Higgs boson couples to fermions (quarks and leptons) through Yukawa interactions
  - **giving masses to quarks and leptons**
- Yukawa interactions are "a new kind of fundamental interaction" -Gavin Salam at LHCP theory summary talk
  - **important to study the Yukawa sector, which may provide important indication for the origin of the fermion mass pattern**
- Experimental signatures: **$t\bar{t}H$ production**, **$H\rightarrow\tau\tau$ decay**, **$H\rightarrow b\bar{b}$ decay**, etc.
  - In SM, Yukawa couplings are proportional to fermion masses; BSM physics can modify coupling strengths



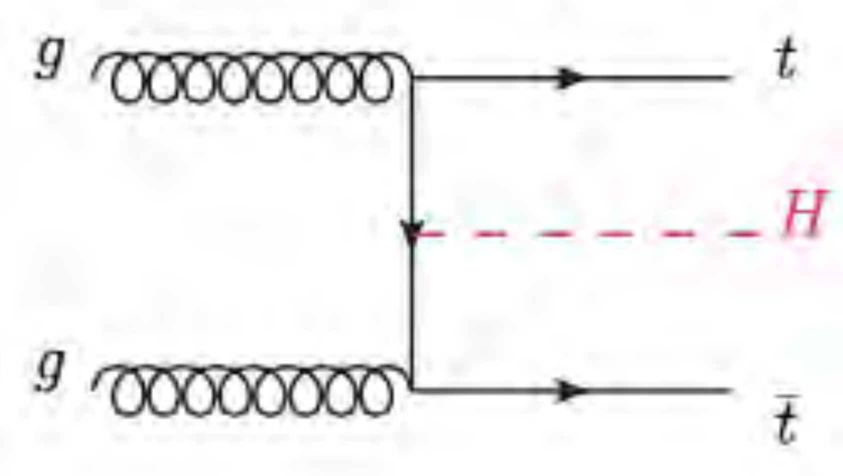
Higgs couplings to top quarks

- An interesting probe: the Yukawa coupling between the Higgs boson and the top quark, the heaviest particle in SM
- Higgs-top Yukawa coupling can be **indirectly probed** via the gluon-fusion production and H→γγ decay (loop-level processes)
  - BSM particles could be present in the loop

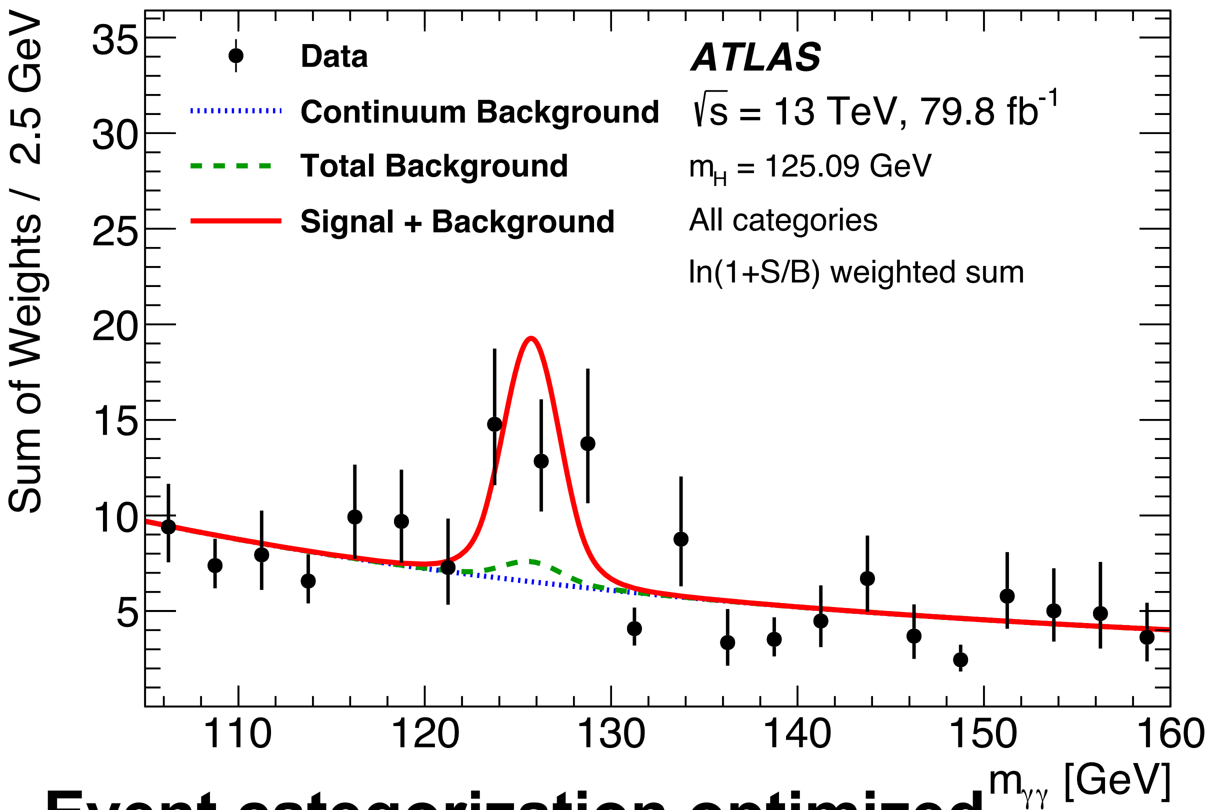


Higgs couplings to top quarks

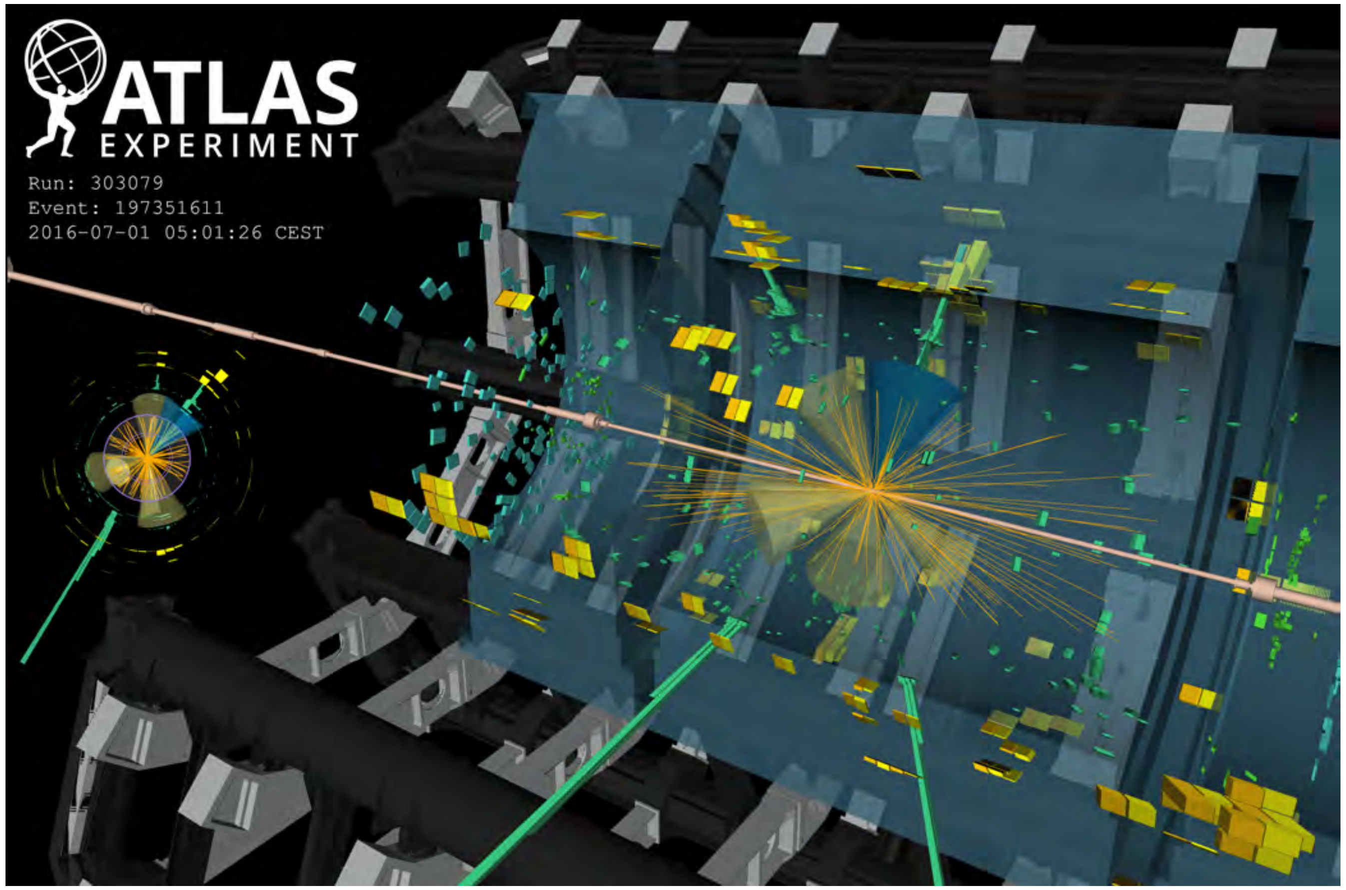
- A **more direct test** of this coupling can be performed through the production of the Higgs boson in association with a top quark pair ($t\bar{t}H$)
- Could get handles on BSM physics by comparison between loop-induced processes and direct $t\bar{t}H$ production
- A very rare Higgs production mode (~1%); mainly a tree-level process
- Need to consider different Higgs boson decay channels ($\gamma\gamma$, WW^*, ZZ^*, $\tau\tau$, $b\bar{b}$) for observing such a rare production mode!



Higgs couplings to top quarks



Event categorization optimized with machine learning (e.g. XGBoost)



Phys. Lett. B 07 (2018) 035

- The observed $t\bar{t}H$ signal significance is **6.3σ** (expected: 5.1σ) in the ATLAS Run 1 + Run 2 combination
- The observed $t\bar{t}H$ signal significance is **5.2σ** (expected: 4.2σ) in the CMS Run 1 + Run 2 combination (using less data)
- **Observation of $t\bar{t}H$ production: constitutes a direct observation of the Higgs-Top Yukawa coupling!**

CERN press release on June 4, 2018

The Higgs boson reveals its affinity for the top quark

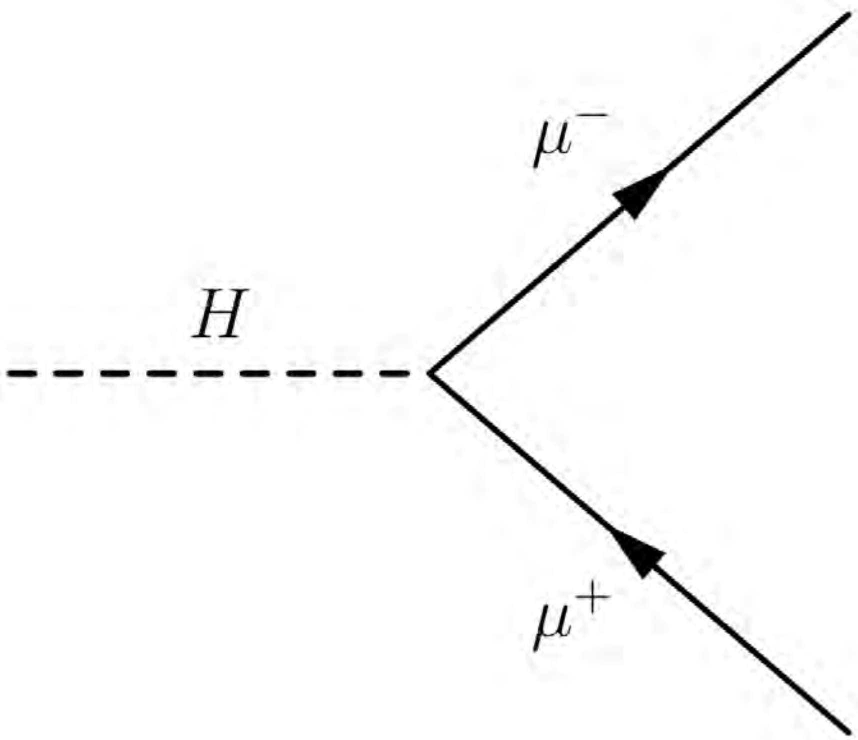
New results from the ATLAS and CMS experiments at the LHC reveal how strongly the Higgs boson interacts with the heaviest known elementary particle, the top quark, corroborating our understanding of the Higgs and setting constraints on new physics.

4 JUNE, 2018

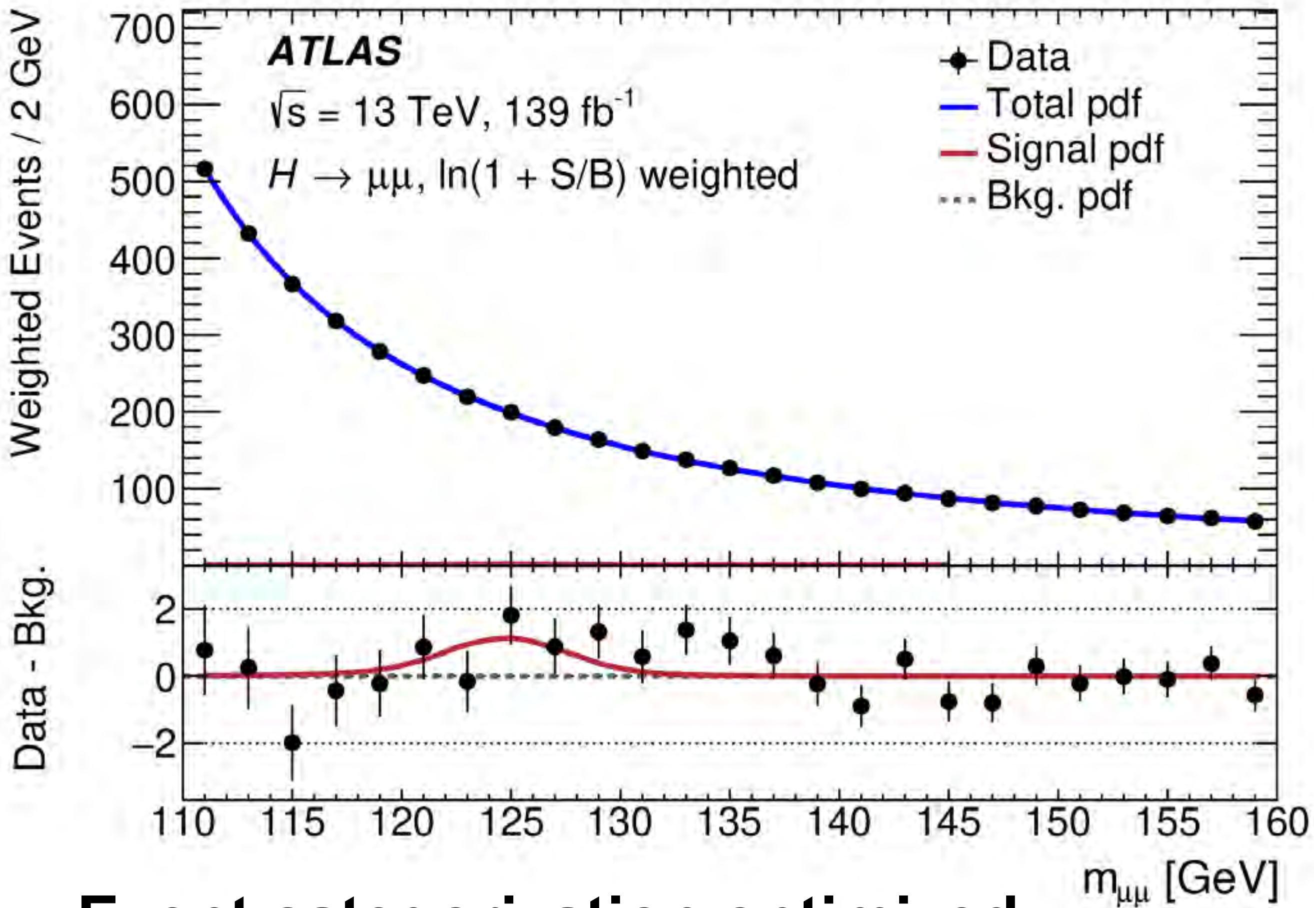
- I was selected to represent the ATLAS collaboration to give a **CERN seminar**, which presents the ATLAS $t\bar{t}H$ observation results to the CERN community:

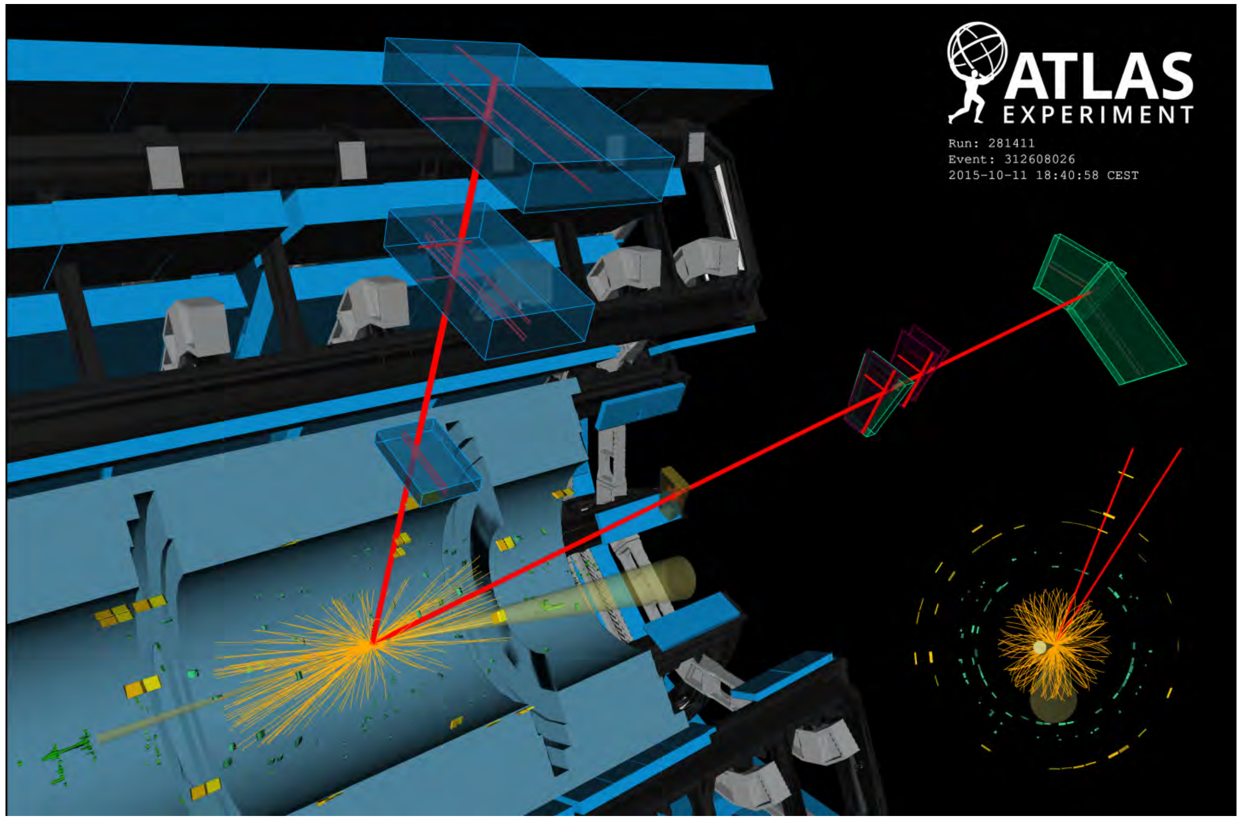
Higgs couplings to muons

- The couplings between the Higgs boson and third-generation fermions (top quark, bottom quark, τ lepton) have already been observed
  - The Higgs couplings with fermions of the other generations have not been established
- The Higgs decay to two muons offers the best opportunity to observe the Higgs couplings with second-generation fermions at the LHC
  - Small branching ratio in SM (2×10^{-4}), physics beyond the SM could modify it
  - The main challenge is a very small signal over background ratio (~0.2%)



Higgs couplings to muons





Event categorization optimized with machine learning (e.g. XGBoost)

Phys. Lett. B 812 (2021) 135980

- The observed H→μμ significance is **2.0σ** (expected 1.7σ) in ATLAS full Run 2 result
  - I made contributions to this
- The observed H→μμ significance is **3.0σ** (expected 2.5σ) in CMS full Run 2 result
- **These results on the H→μμ decay provide first evidence for the Higgs couplings to second generation fermions**

Higgs couplings to muons

CERN press release on August 3, 2020

CERN experiments announce first indications of a rare Higgs boson process

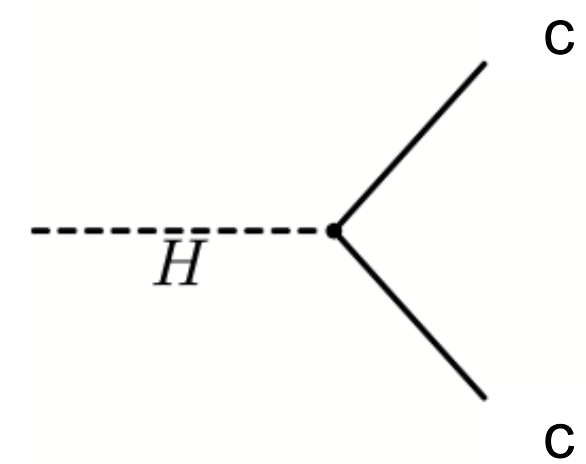
The ATLAS and CMS experiments at CERN have announced new results which show that the Higgs boson decays into two muons

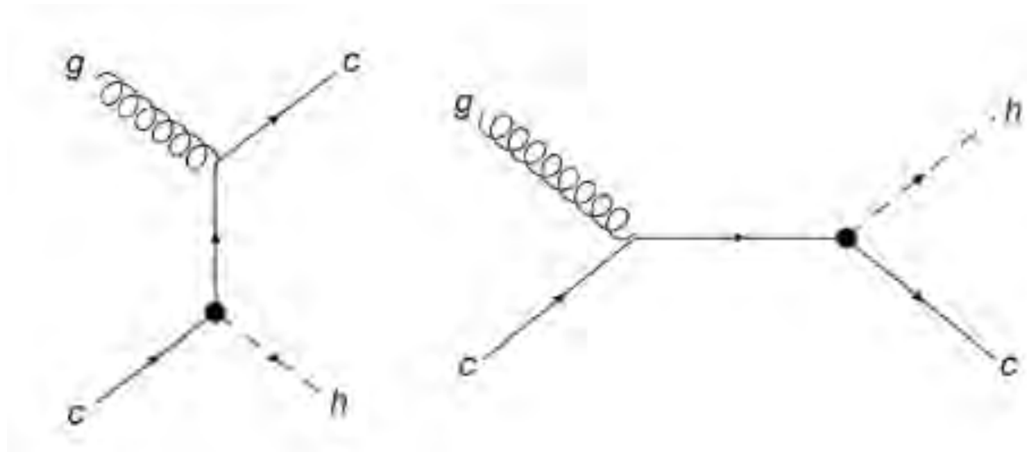
3 AUGUST, 2020

- **Will hopefully observe the H→μμ decay with more than 5σ in Run 3**
  - I am currently working on this

Higgs couplings to c quarks

- H→c$\bar{c}$ decay is currently the main channel to probe Higgs coupling to c quarks
  - Limit on H→c$\bar{c}$ signal using Run 2 data: 26 (ATLAS) and 14 (CMS) times SM prediction
- We need to improve the experimental sensitivity. One possibility is to look for Higgs+c production
  - I am studying this new experimental channel with PKU colleagues

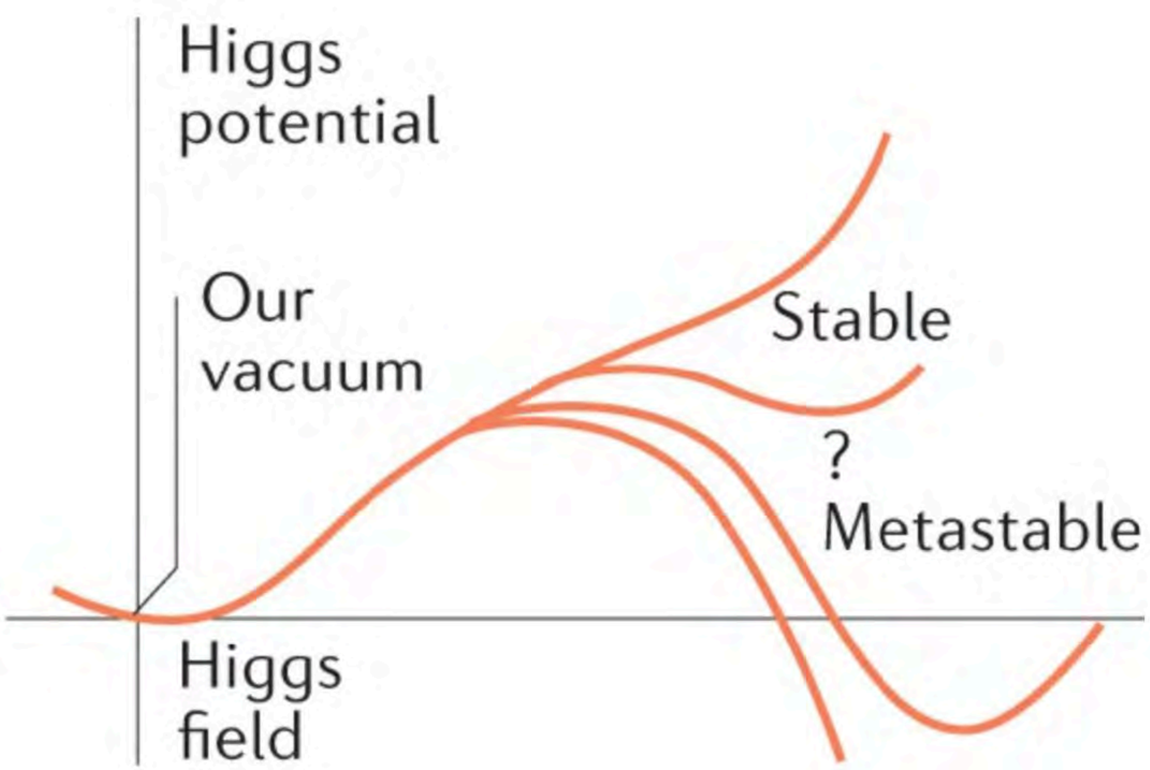


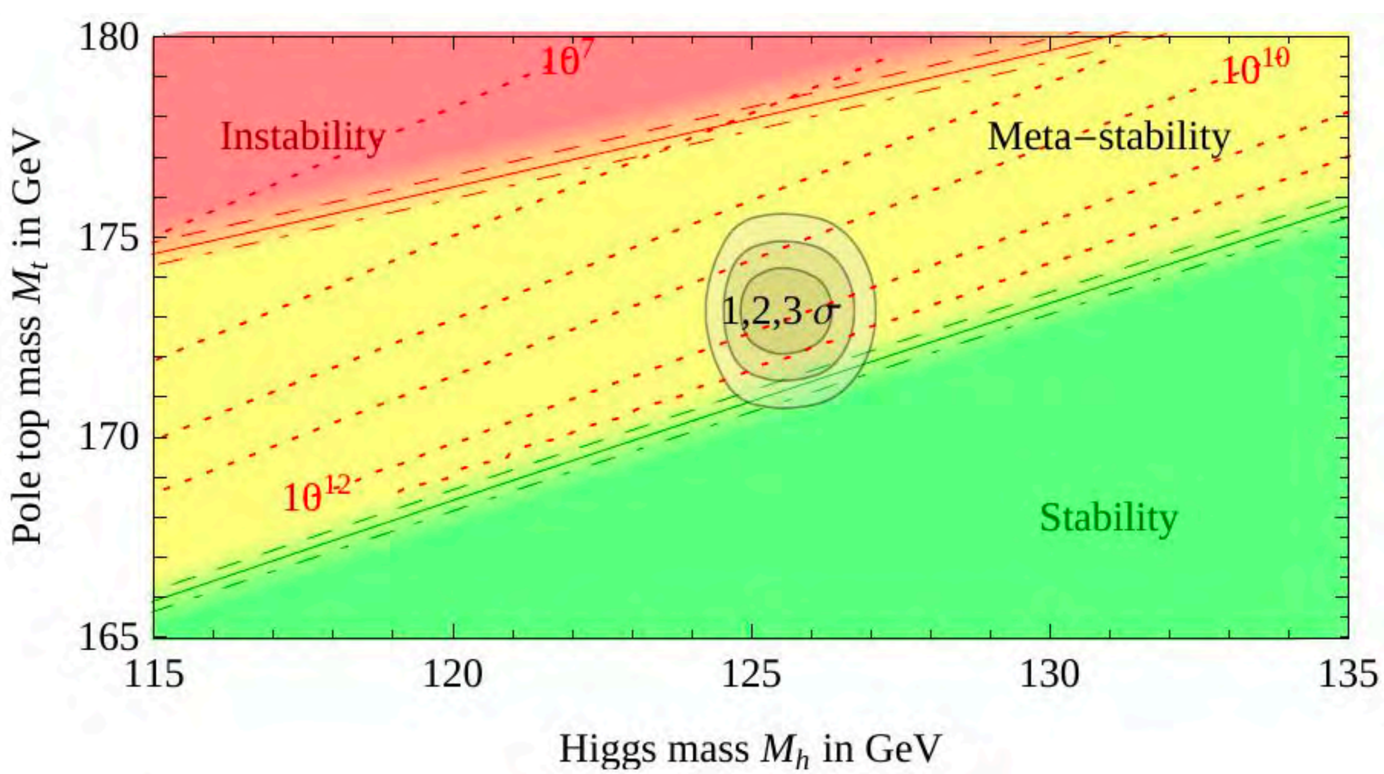


Higgs boson self-couplings

Vacuum stability

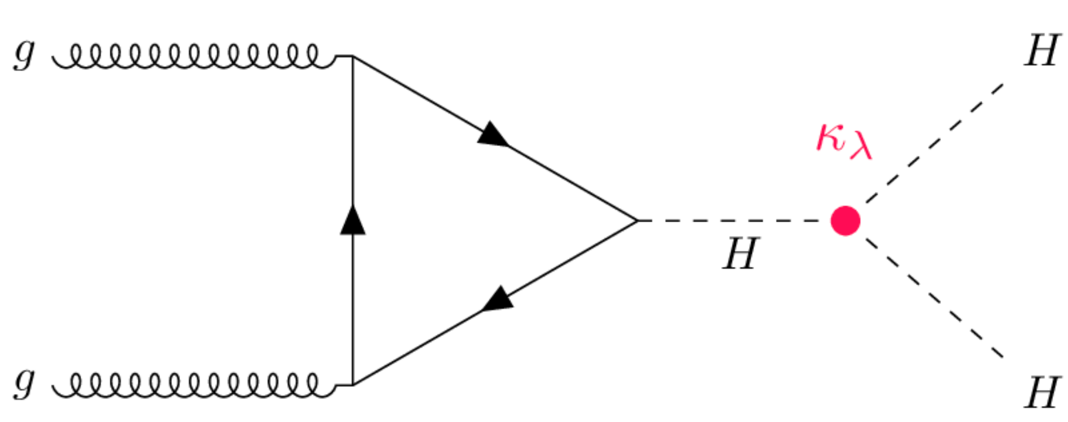
- Quantum correction can change the shape of Higgs potential, the vacuum may develop a second minimum
- The stability of vacuum depends on Higgs mass and top mass, the Higgs vacuum of the SM sit very close to the border between stable and metastable
- It might suggest something deeper about the origin of the SM

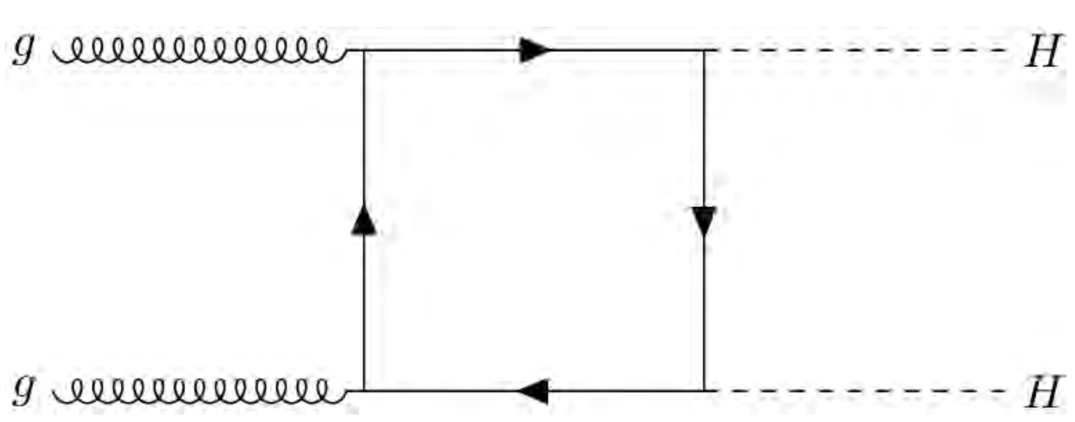




Higgs boson self-couplings

- **Higgs self-coupling is one of the deepest questions of the SM** and may provide a portal to new physics beyond it
  - Vacuum stability, early universe evolvement, …
- **Double Higgs production is the way to directly probe Higgs self-couplings at the LHC**
- Extremely low cross-section in the SM
  - (one double-Higgs event for every 1000 single-Higgs events)
- Non-SM self-coupling strength can change cross-section and kinematics of double Higgs production



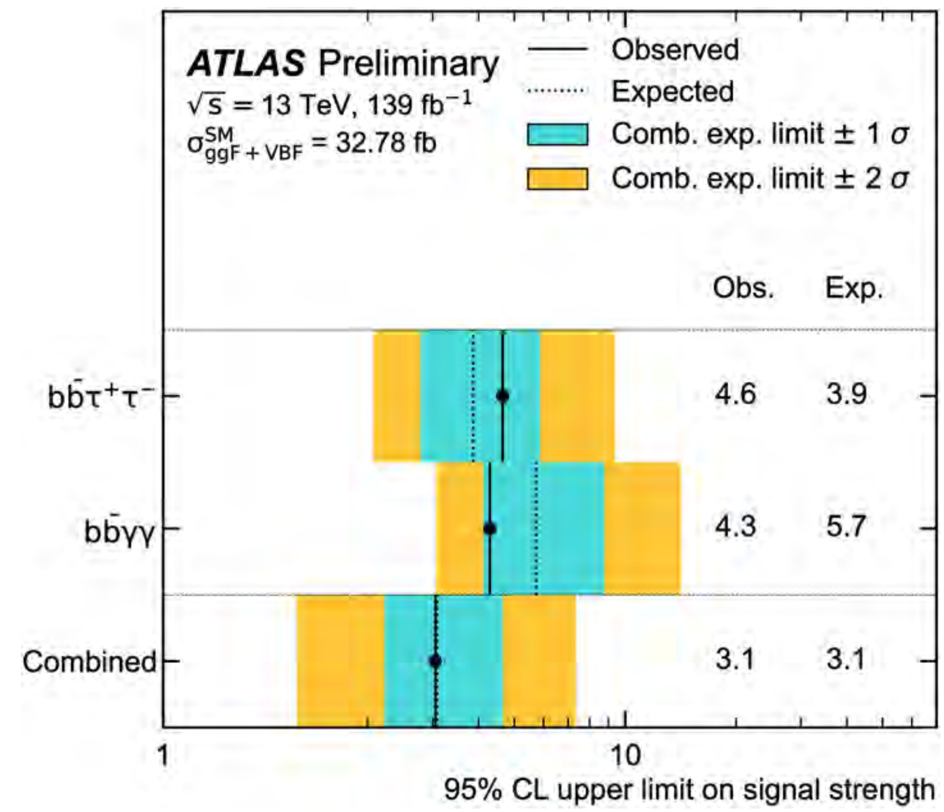


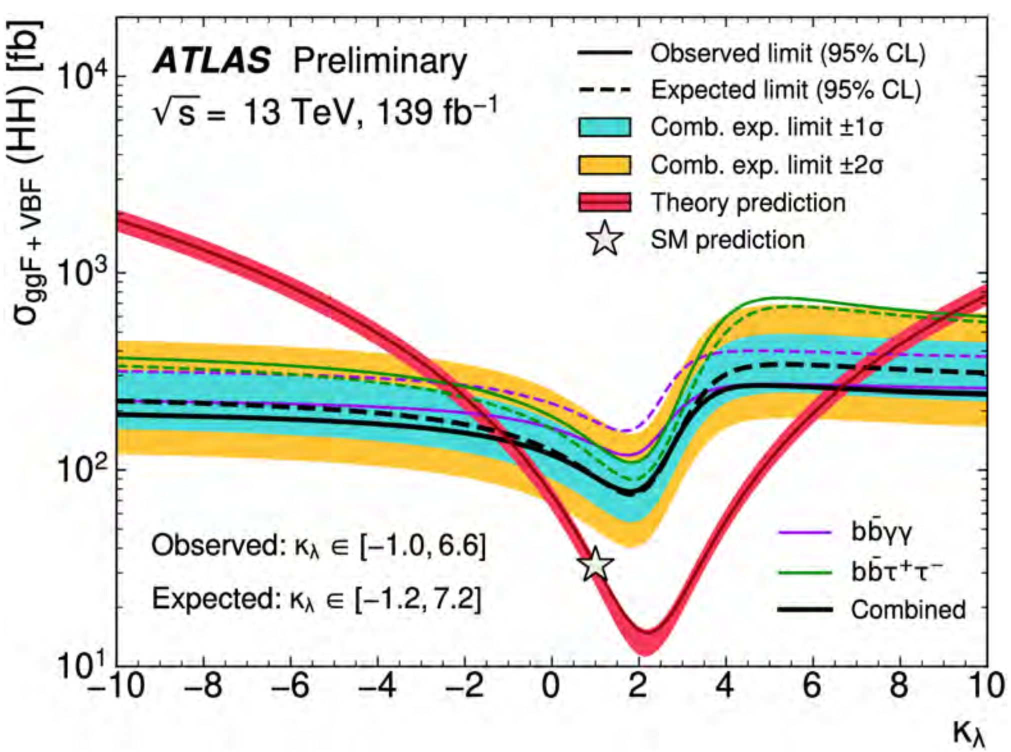
Higgs boson self-couplings

- Perform double Higgs search with decay channels of HH→bbγγ, HH→bb$\tau\tau$, HH→bbbb, etc

- ATLAS combined analysis gives the world's currently best constraints
  - Observed (expected) limit of double Higgs cross section: 3.1 (3.1) times SM prediction
  - Observed (expected) constrain on self-coupling strength: $-1.0<\kappa_\lambda<6.6$ ($-1.2<\kappa_\lambda<7.2$)
  - I contributed to ATLAS Run 2 HH analyses

- Towards establishing Higgs self-coupling
  - should reach at least 4 standard deviations for double Higgs production at HL-LHC
  - I plan to contribute to CMS HH analyses in the long term





ATLAS-CONF-2021-052

Measured properties of the Higgs Boson

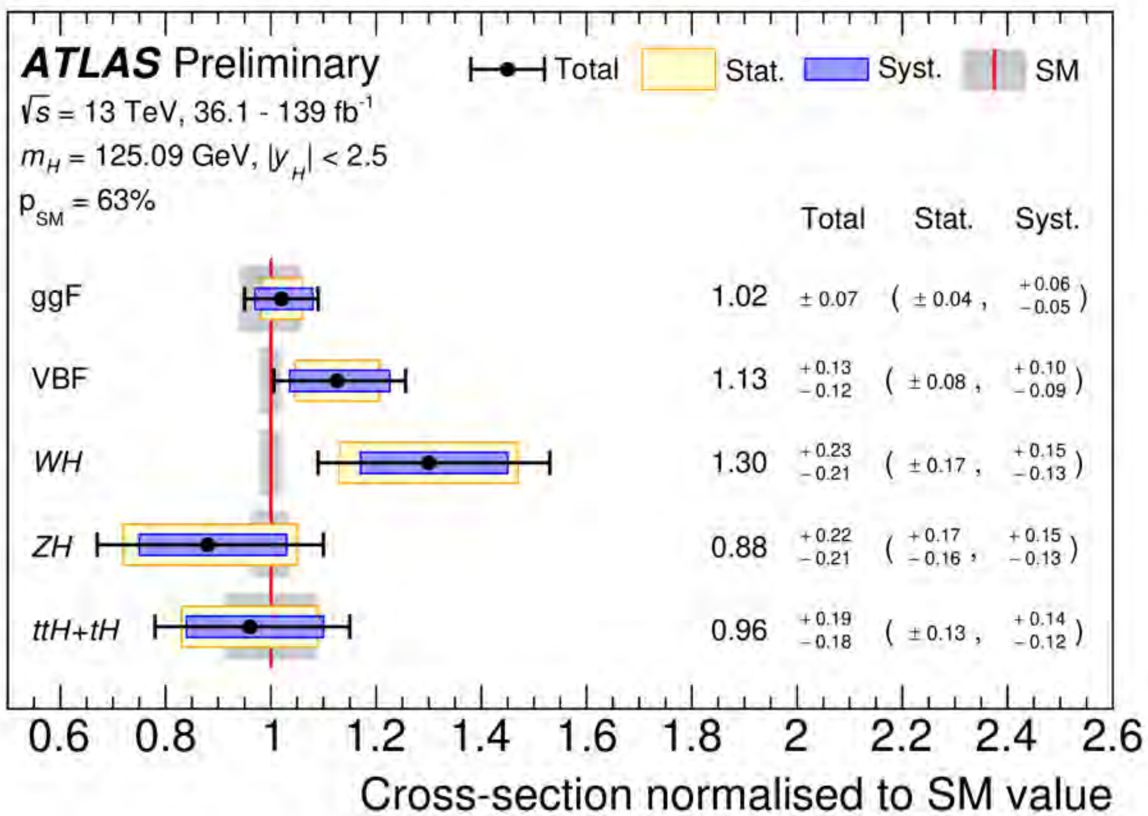
Combined measurements of Higgs coupling properties

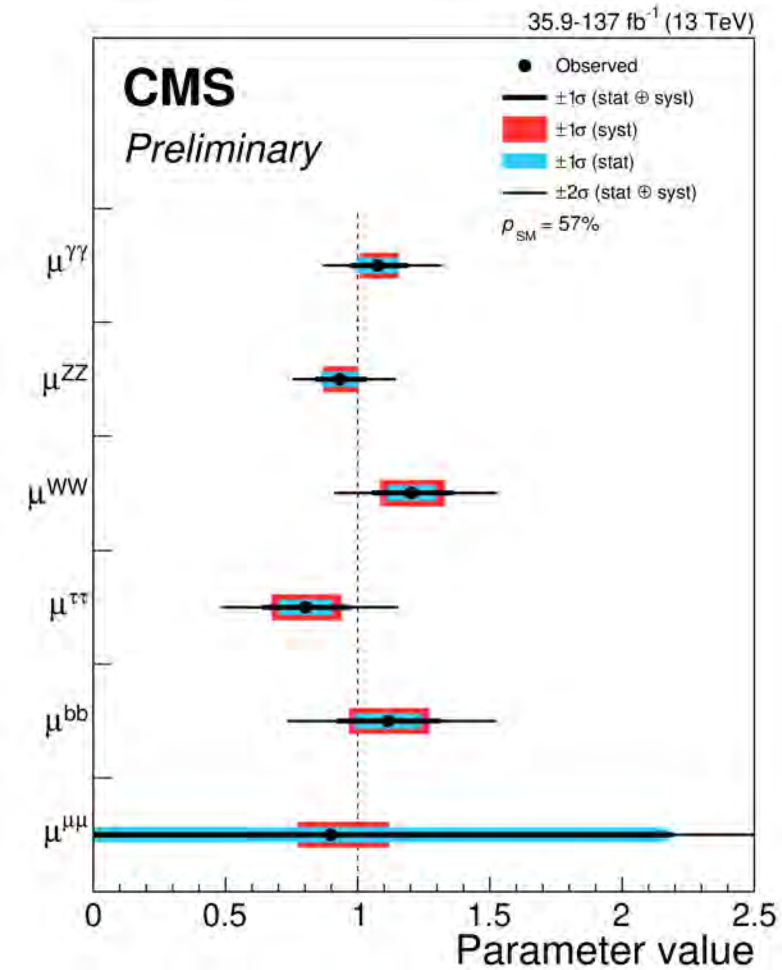
	ggF	VBF	VH	ttH+tH
H→γγ	✔ (139 fb^{-1}) ✔ (77 fb^{-1})	✔ (139 fb^{-1}) ✔ (77 fb^{-1})	✔ (139 fb^{-1})	✔ (139 fb^{-1}) ✔ (77 fb^{-1})
H→ZZ	✔ (139 fb^{-1}) ✔ (137 fb^{-1})	✔ (139 fb^{-1}) ✔ (137 fb^{-1})	✔ (139 fb^{-1}) ✔ (137 fb^{-1})	
H→WW	✔ (139 fb^{-1}) ✔ (36 fb^{-1})	✔ (139 fb^{-1}) ✔ (36 fb^{-1})	✔ (36 fb^{-1})	✔ (36-139 fb^{-1}) ✔ (77-139 fb^{-1})
H→ττ	✔ (139 fb^{-1}) ✔ (77 fb^{-1})	✔ (139 fb^{-1}) ✔ (77 fb^{-1})	✔ (139 fb^{-1}) ✔ (77 fb^{-1})	
H→bb	✔ (36 fb^{-1})	✔ (126 fb^{-1}) ✔ (77 fb^{-1})	✔ (139 fb^{-1}) ✔ (77 fb^{-1})	✔ (139 fb^{-1}) ✔ (77 fb^{-1})
H→μμ	✔ (139 fb^{-1}) ✔ (36 fb^{-1})	✔ (139 fb^{-1}) ✔ (36 fb^{-1})	✔ (139 fb^{-1})	✔ (139 fb^{-1})
H→Zγ	✔ (139 fb^{-1})	✔ (139 fb^{-1})	✔ (139 fb^{-1})	✔ (139 fb^{-1})
H→invisible		✔ (139 fb^{-1})		

✔: channel included in the ATLAS combination
✔: channel included in the CMS combination

Production and decay rates

ATLAS-CONF-2021-053 | [CMS-PAS-HIG-19-005](CMS-PAS-HIG-19-005)



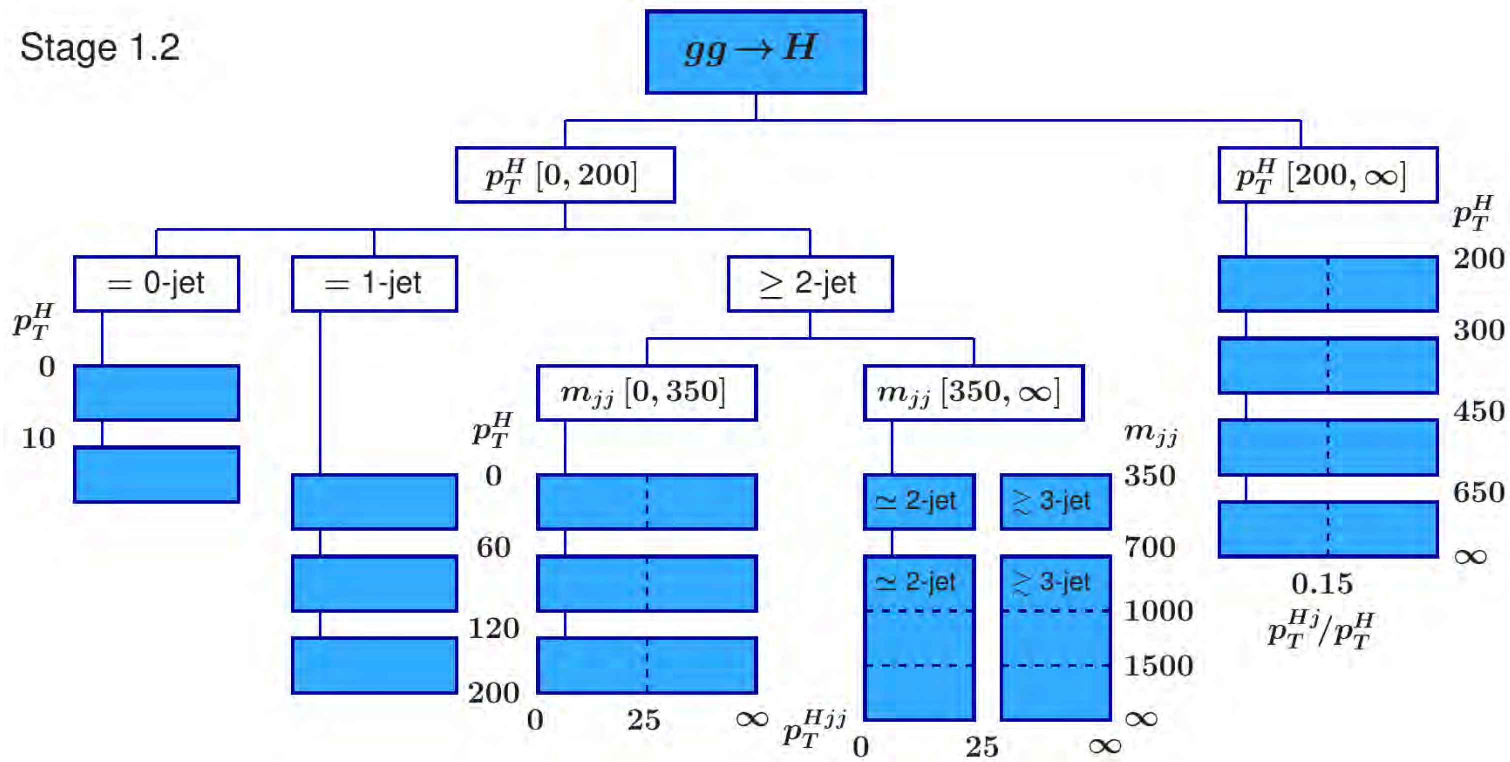


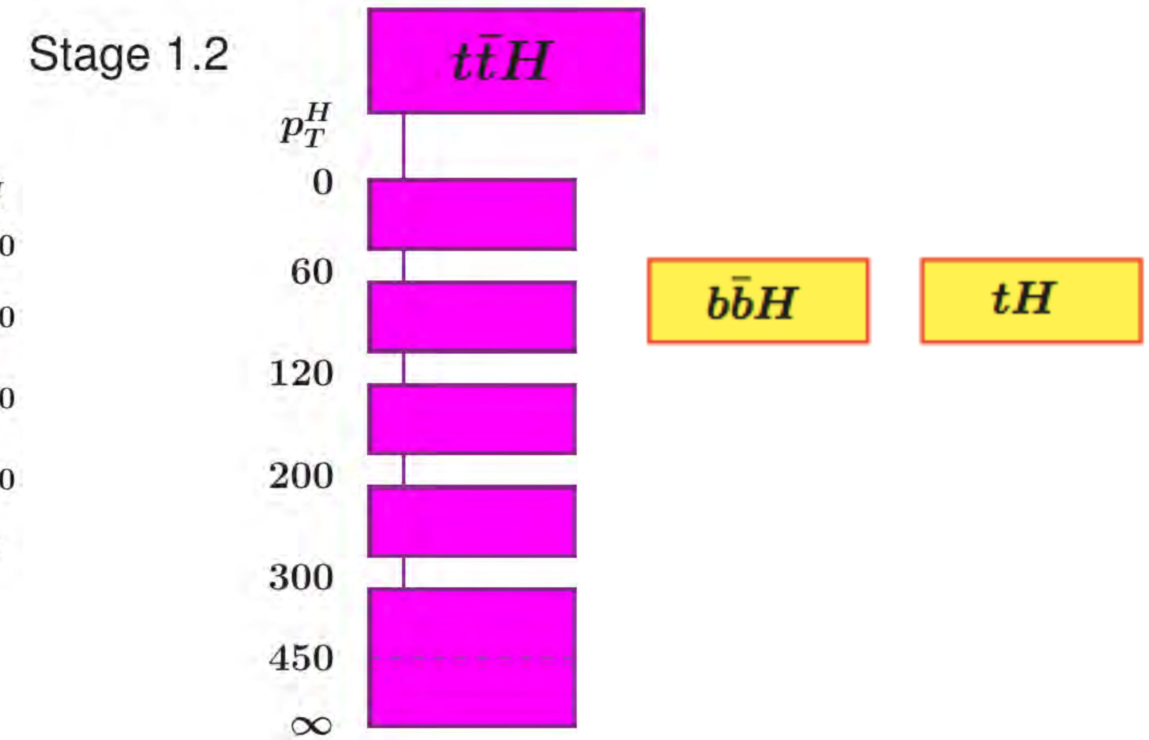
- ggF cross section is now measured with 7% precision
    - Precision of N3LO cross section prediction: 5%
- All major production modes (ggF, VBF, WH, ZH, ttH) and decay modes ($H\to\gamma\gamma$, $H\to ZZ$, $H\to WW$, $H\to\tau\tau$, $H\to bb$) are observed

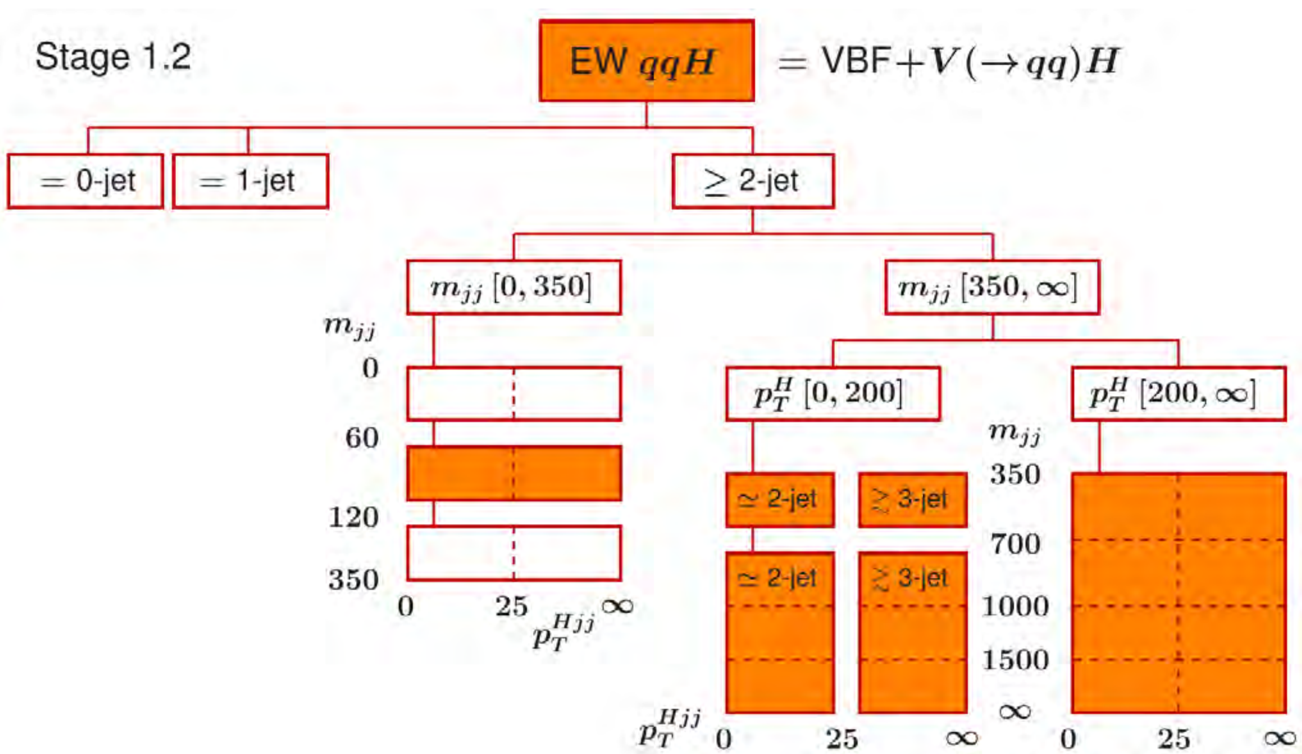
Simplified template cross section (STXS)

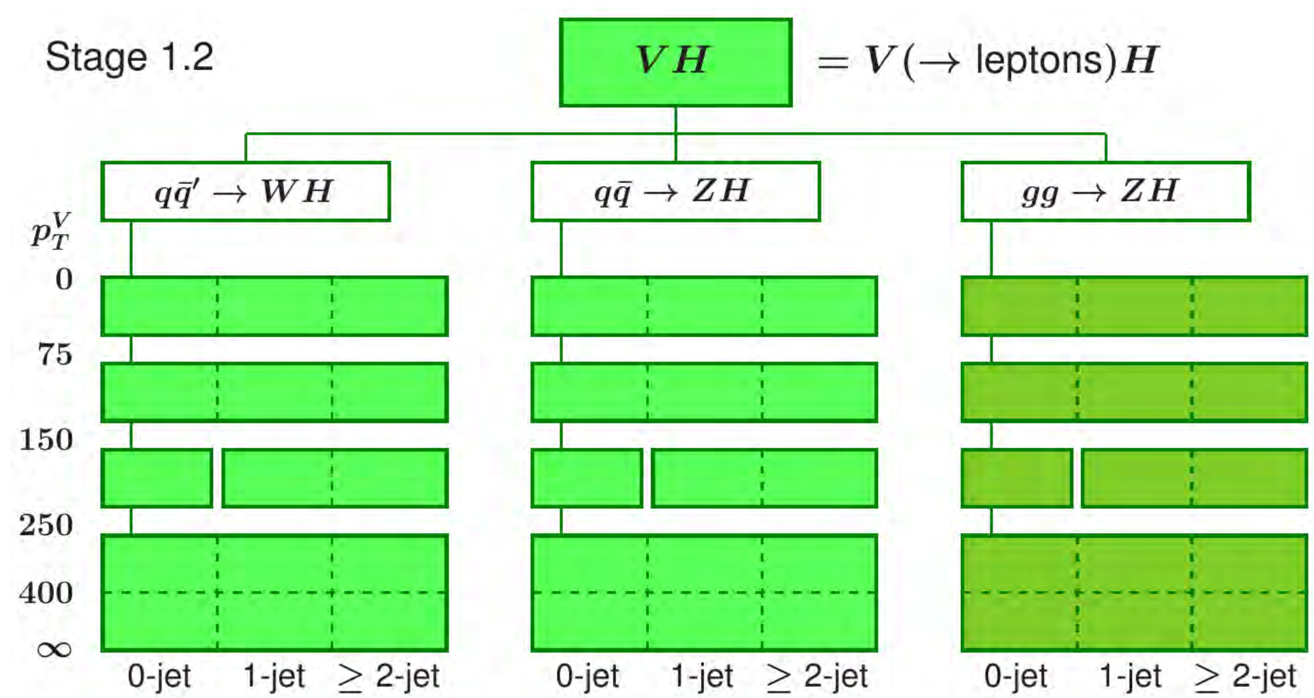
- Simplified template cross section (STXS) is the common framework for the LHC Higgs coupling property measurements in Run 2
    - Split production mode cross-sections into various phase-space regions, which are chosen according to sensitivity to beyond Standard Model effects, avoidance of large theory uncertainties, matching to experimental selections
    - For each STXS region, use the SM predicted signal templates to fit data; can still exploit powerful analysis techniques (e.g. MVA)
    - STXS measurements can be used to probe coupling modifiers (“kappa”) and effective field theories (EFT)

Stage 1.2 STXS

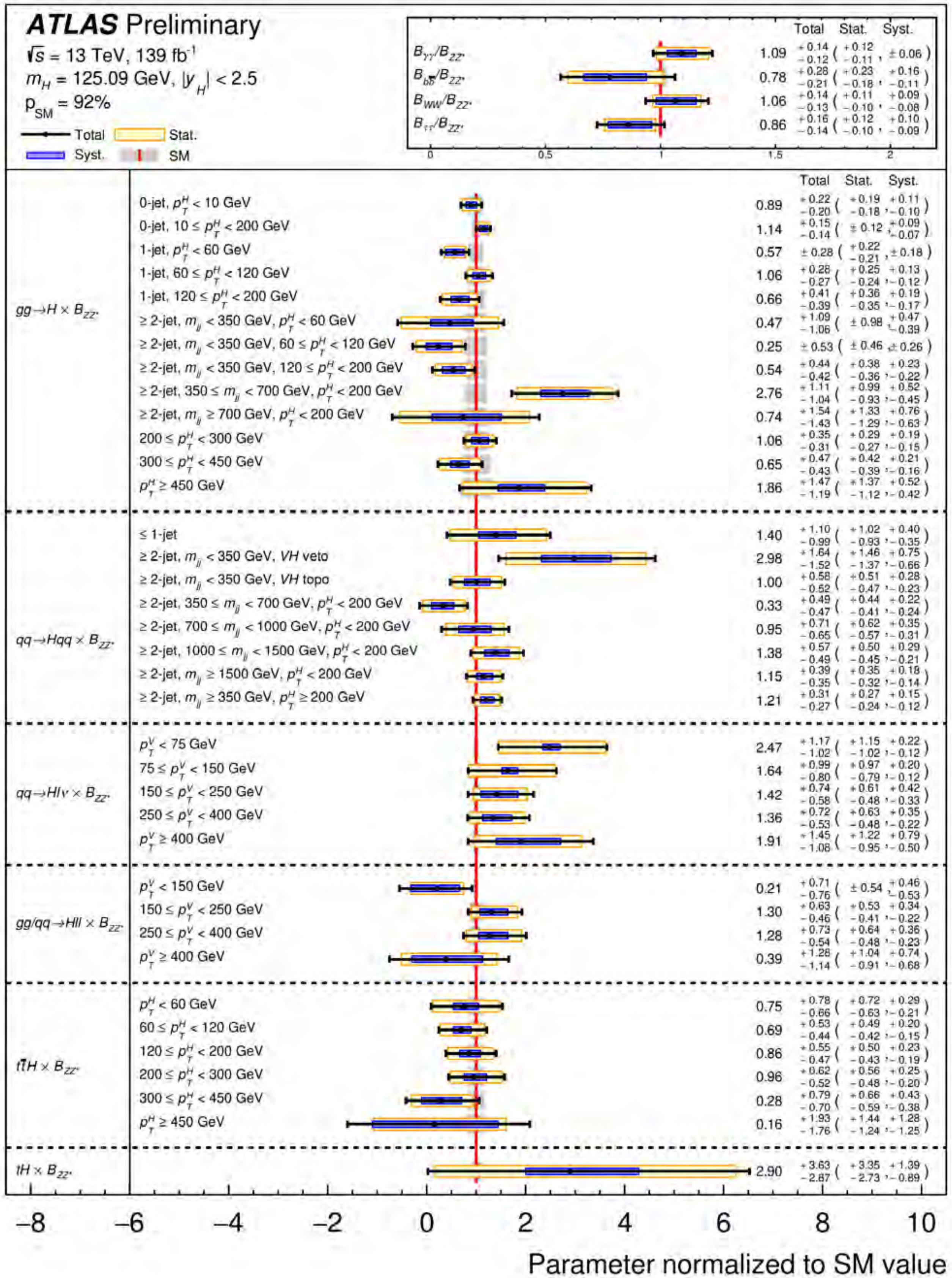








STXS results (w/o assuming the SM decays)

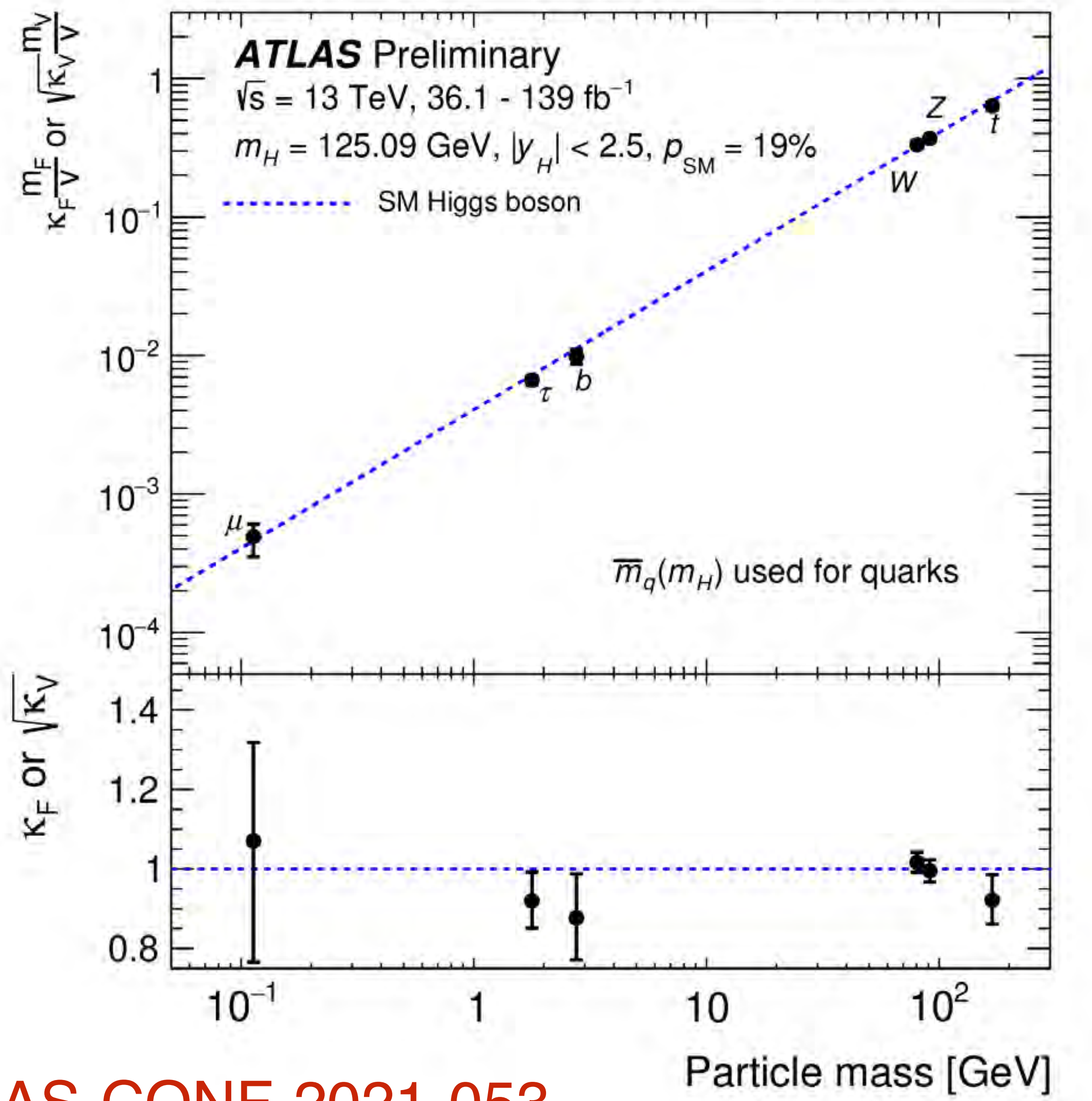


ATLAS-CONF-2021-053

- STXS are measured granularly in this combination: 41 regions are probed
  - VBF, ggF+2jets: granular in mass(jj)
  - VH: reach high pT(V)
  - ttH: reach high pT(H)
- All regions are statistically limited; in some regions (e.g. ggF 0/1-jet) systematics are not negligible

Coupling modifier

- "Kappa" framework: assign coupling modifier to each interaction vertex (e.g. κ_W, κ_t…)
- Good agreement with the SM across 3 orders of magnitude of particle mass
- One of the most prominent achievements to date at the LHC



ATLAS-CONF-2021-053

- I contributed to the ATLAS Run 2 Higgs coupling property measurements
  - I plan to work on the CMS Run 3 Higgs coupling property measurements using new analysis techniques

Higgs mass/width/spin/CP

- **Higgs mass** is the only free parameter in the SM Higgs sector. Measured in channels with best resolution: H→ZZ*→4l and H→γγ
  - ATLAS+CMS Run 1: 125.09 ± 0.24 GeV
  - CMS Run 1+partial Run 2: 125.38 ± 0.14 GeV
  - ATLAS Run 1+partial Run 2: 124.97 ± 0.24 GeV

- SM prediction of **Higgs width**: 4.1 MeV
  - direct measurement limited by detector resolution
- Constrain Higgs width by comparing on-shell and off-shell Higgs rates using H→ZZ*→4l and H→ZZ*→2l2ν
  - determined to be $3.2^{+2.4}_{-1.7}$ MeV
- In γγ channel, interference between Higgs signal and continuous background can cause Higgs mass shift
  - this effect can also constrain Higgs width

Higgs mass/width/spin/CP

- The SM Higgs boson is a scalar: **spin**-zero, **CP**-even
- The observed boson was verified to be spin-zero in Run 1
- Non-CP-even couplings of the Higgs boson were searched using ggF+2j, VBF, VH and ttH productions and H→ZZ, H→WW and H→$\tau\tau$ decays.
  - Data disfavor the pure CP-odd scenario, stringent constraints on CP mixing are given

- I did not directly work on mass/width/spin/CP analyses, but oversaw several such analyses as the ATLAS Higgs-Gamma subgroup convener

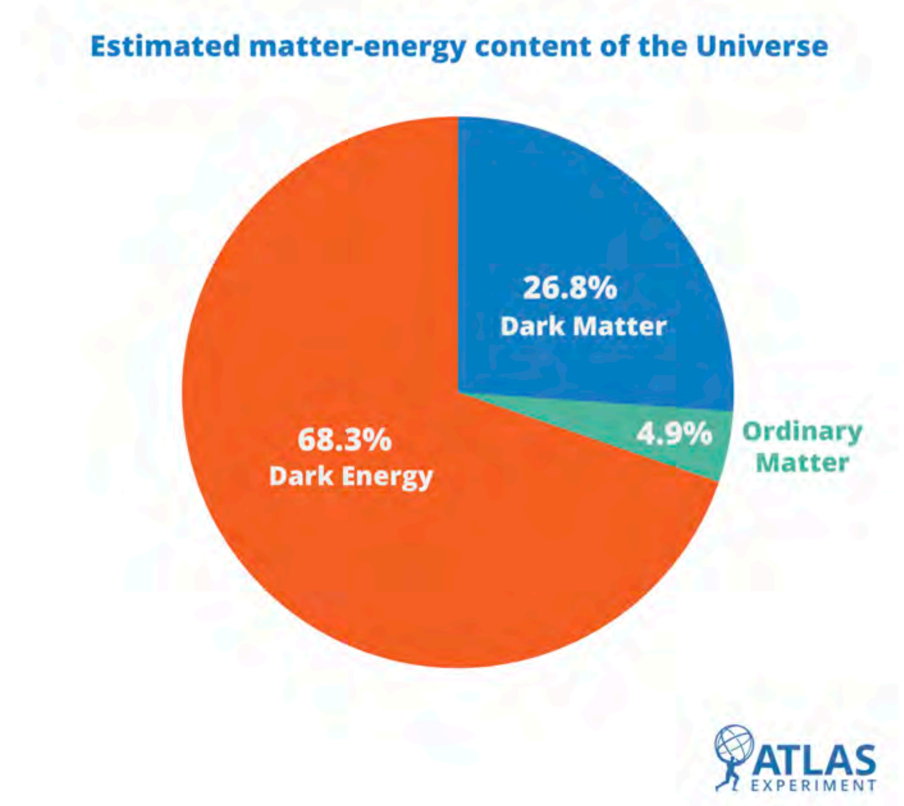
Higgs boson and cosmology

Higgs boson and cosmology

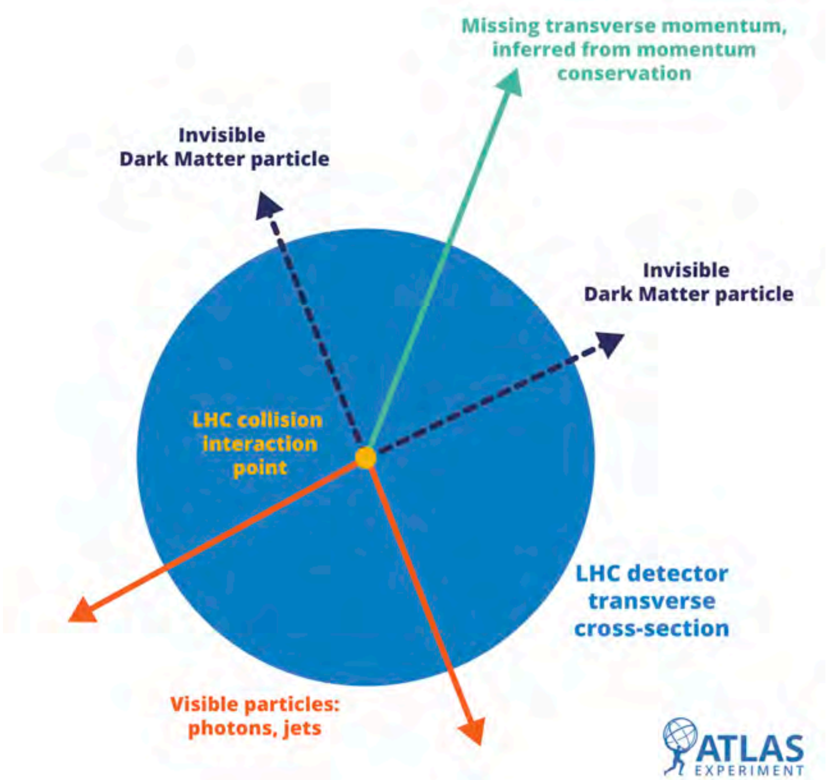
- Higgs boson is central to our understanding of the universe, pertaining to:
  - Origin of matter-antimatter asymmetry
  - Primordial inflation
  - Nature of Dark Energy
  - Nature of Dark Matter

Dark Matter @ LHC

- Dark Matter comprises most of the mass of the Universe according to astrophysics measurements
  - But the nature of Dark Matter remains largely unknown

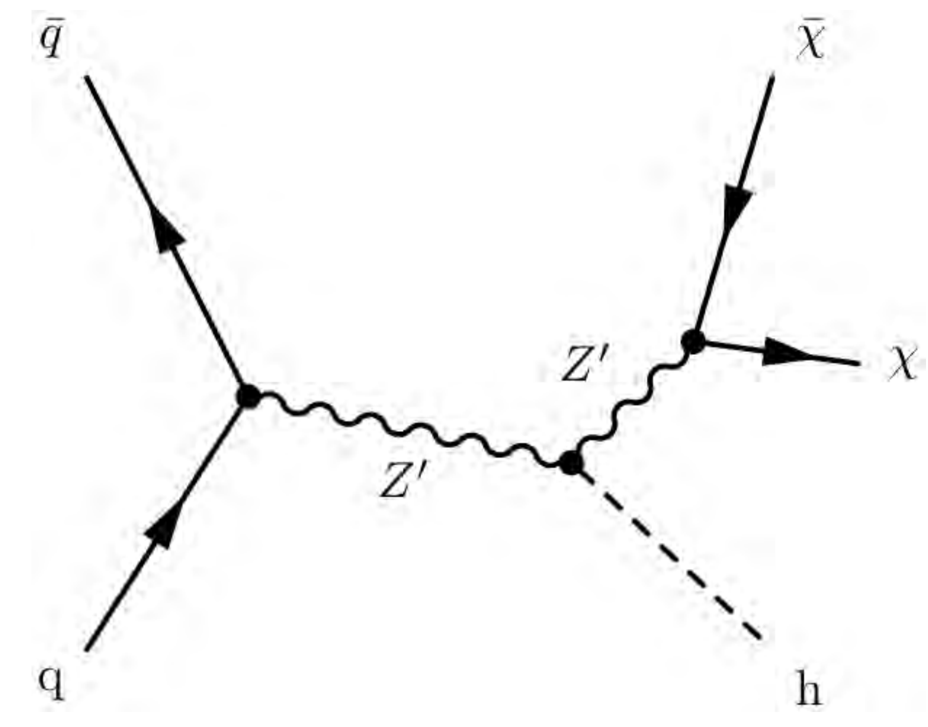


- If Dark Matter has weak interaction with known particles, it can be produced at the LHC
  - They would not leave a visible signature in the detectors
  - Look for visible objects (e.g. jets, photons) plus large missing transverse momentum from Dark Matter

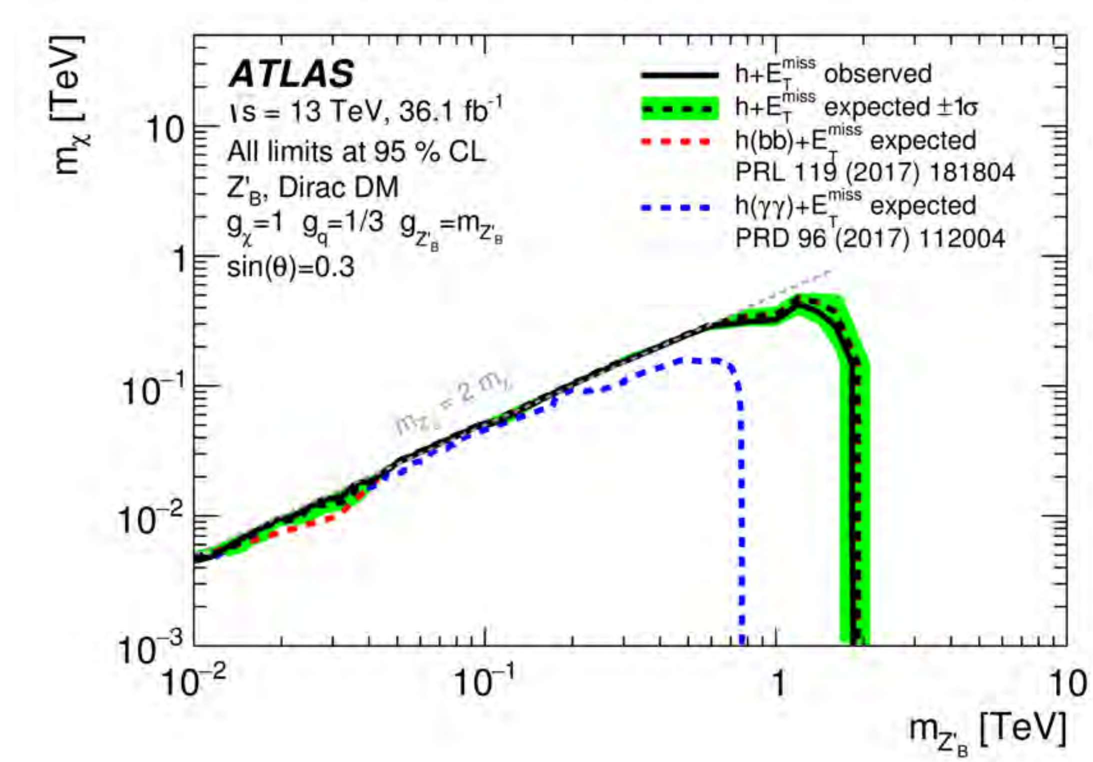


mono-Higgs Dark Matter search

- Following the Higgs discovery, mono-Higgs signature has opened up a new path to discover Dark Matter



- Given no significant excess in current mono-Higgs results, they are interpreted as strong constraints for the baryonic Z' model and other Dark Matter models

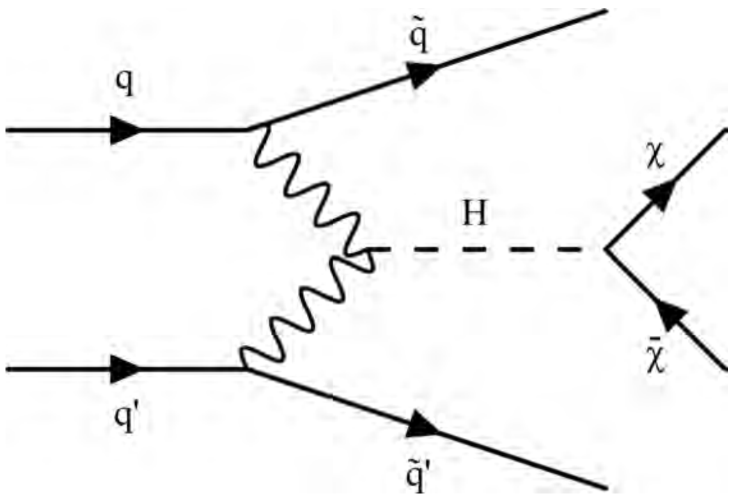


- My work in Run 2

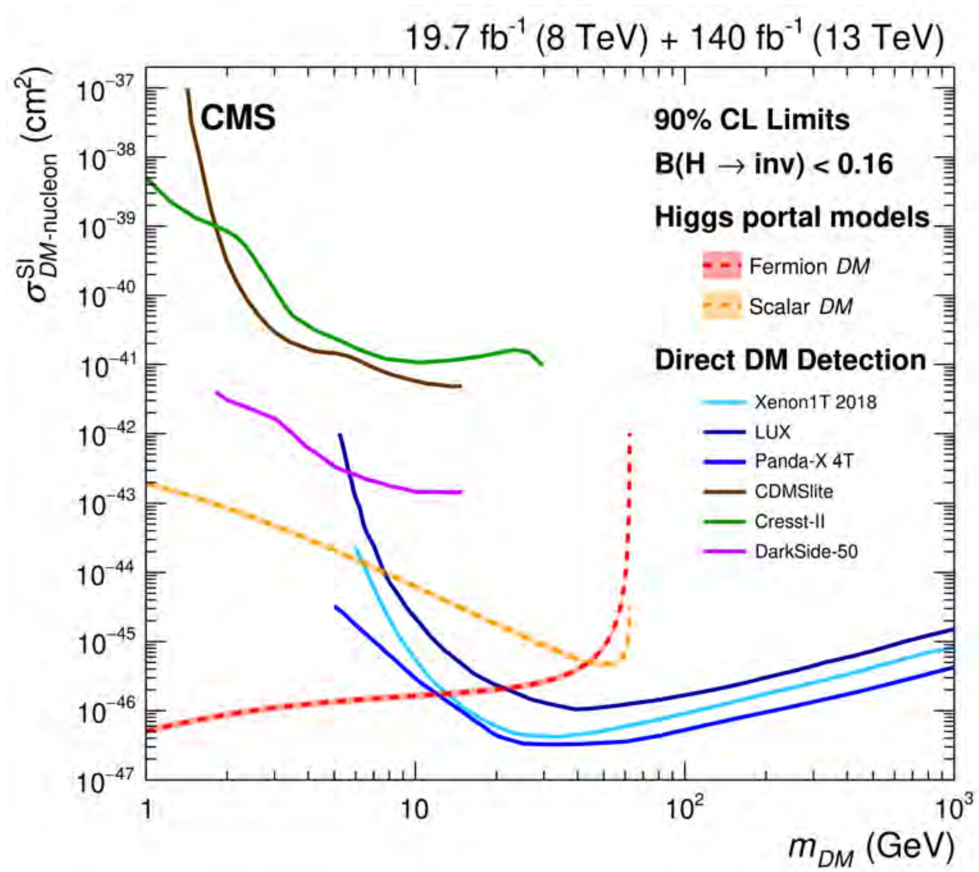
JHEP 05 (2019) 142

Higgs→invisible Dark Matter search

- Higgs→invisible decay is favored by so-called "Higgs portal" model
  - where Dark Matter interacts with known particles through the Higgs boson



- Run 2 Higgs→invisible results:
  - ATLAS: BR<11%
  - CMS: BR<17%
- Results are interpreted as as limit on DM-nucleon scattering in Higgs portal model



- My interest in Run 3

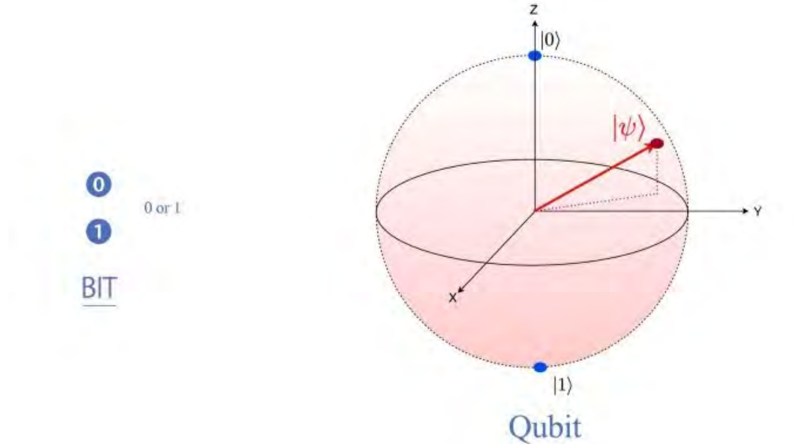
arxiv:2201.11585

Application of quantum machine learning to Higgs physics analyses

Machine learning for HEP

- Machine Learning: "application of artificial intelligence that provides systems the ability to automatically learn and improve from experience without being explicitly programmed"
  - It has become one of the most popular and powerful techniques and tools for High Energy Physics (HEP) data analysis
  - It greatly enhances our ability to identify rare signal against immense backgrounds: important for discovery of new physics
- Issues raised by machine learning
  - Heavy CPU time is needed to train complex models
    - The training time increases with more data
  - May lead to local optimization, instead of global optimization

Quantum machine learning

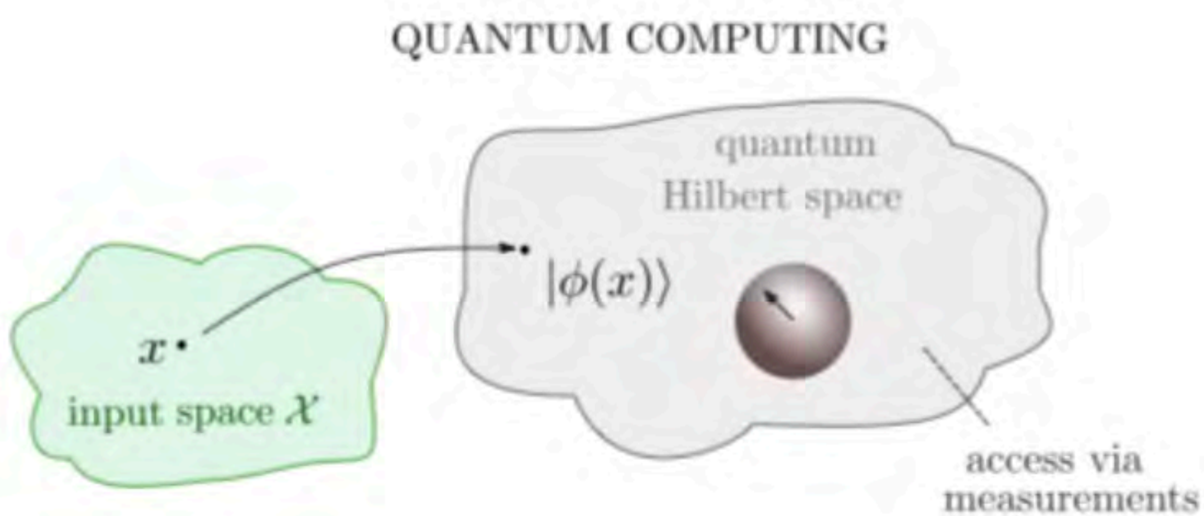


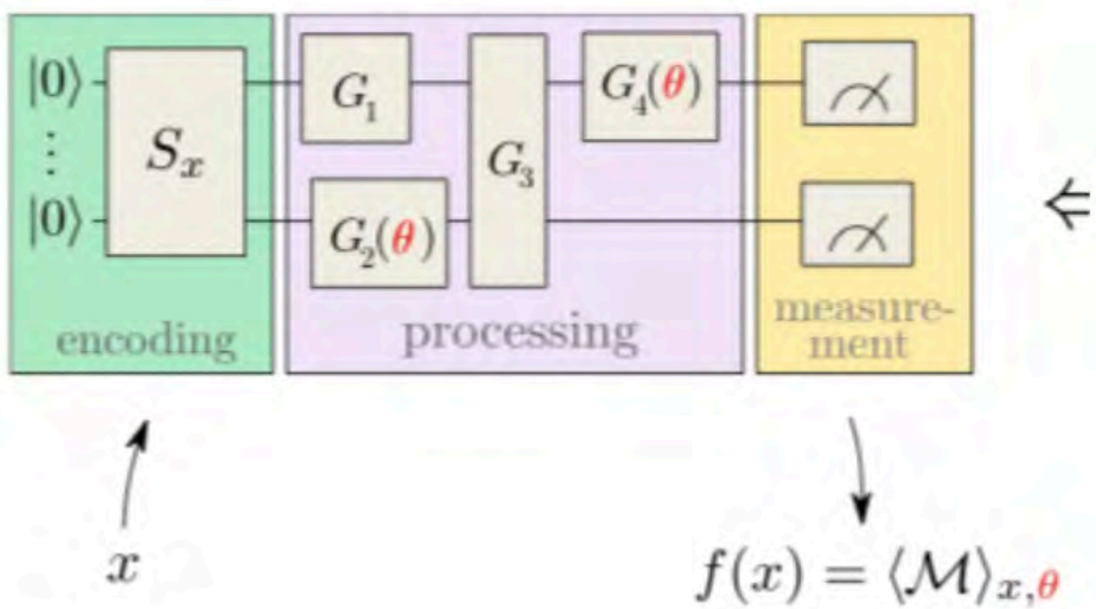
- Quantum computing
  - Perform computation using the quantum state of qubits
  - A way of parallel execution of multiple processes
  - Can speed up certain types of problems effectively

- Quantum machine learning
  - Intersection between machine learning and quantum computing
  - May lead to more powerful solutions and offer a computational "speed up", by exploiting the high dimensional quantum state space through the action of superposition, entanglement, etc
  - Quantum machine learning could possibly become a valuable alternative to classical machine learning for HEP data analysis

Quantum machine learning

- **Quantum machine learning algorithms encode input data to a quantum state, "process" (transform) the quantum state, and access the quantum state via measurements**





Maria Schuld arXiv:2101.11020

Quantum machine learning for HEP

- I have been working to perform High Energy Physics flagship analyses with Quantum Machine Learning methods (Variational Quantum Classifier, Quantum SVM Kernel Method, Quantum Neural Network)
  - on gate-model quantum computer systems (from IBM, Google, 本源)

- Goal: to demonstrate that the potential of quantum computers can be a new computational paradigm for big data analysis in HEP, as a proof of principle

Example 1: Employing Variational Quantum Classifier for ttH and H → μμ analyses

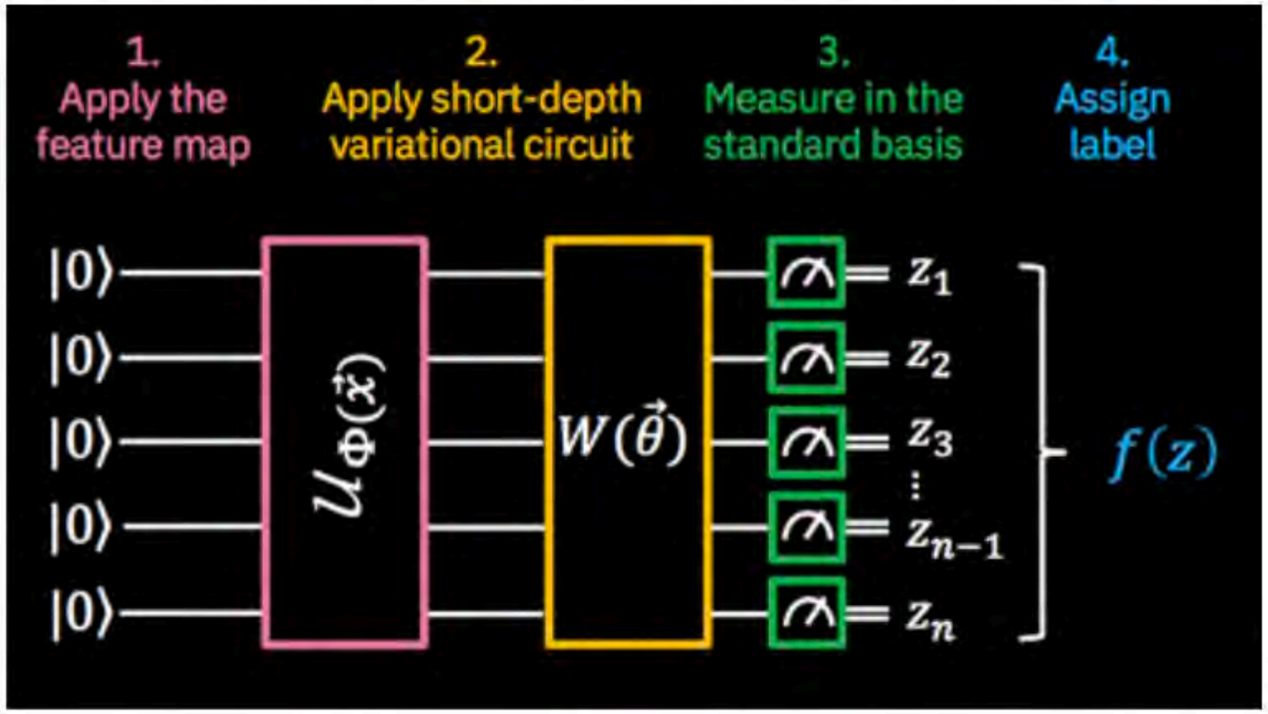
<u>J. Phys. G: Nucl. Part. Phys. 48 125003 (2021)</u>

Variational Quantum Classifier

- In 2018, a Variational Quantum Classifier method was introduced by IBM, published in Nature 567 (2019) 209.
- The Variational Quantum Classifier method can be summarized in four steps.

Variational Quantum Classifier

- 1. Apply feature map circuit $U_{\Phi(\vec{x})}$ to encode input data $\vec{x}$ into quantum state $|\Phi(\vec{x})\rangle$
- 2. Apply short-depth quantum variational circuit W(θ) which is parameterized by gate angles θ
- 3. Measure the qubit state in the standard basis (standard basis: $|0\rangle$, $|1\rangle$ for 1 qubit; $|00\rangle$, $|01\rangle$, $|10\rangle$, $|11\rangle$ for 2 qubits; ...)
- 4. Assign the label ("signal" or "background") to the event through the action of a diagonal operator f in the standard basis



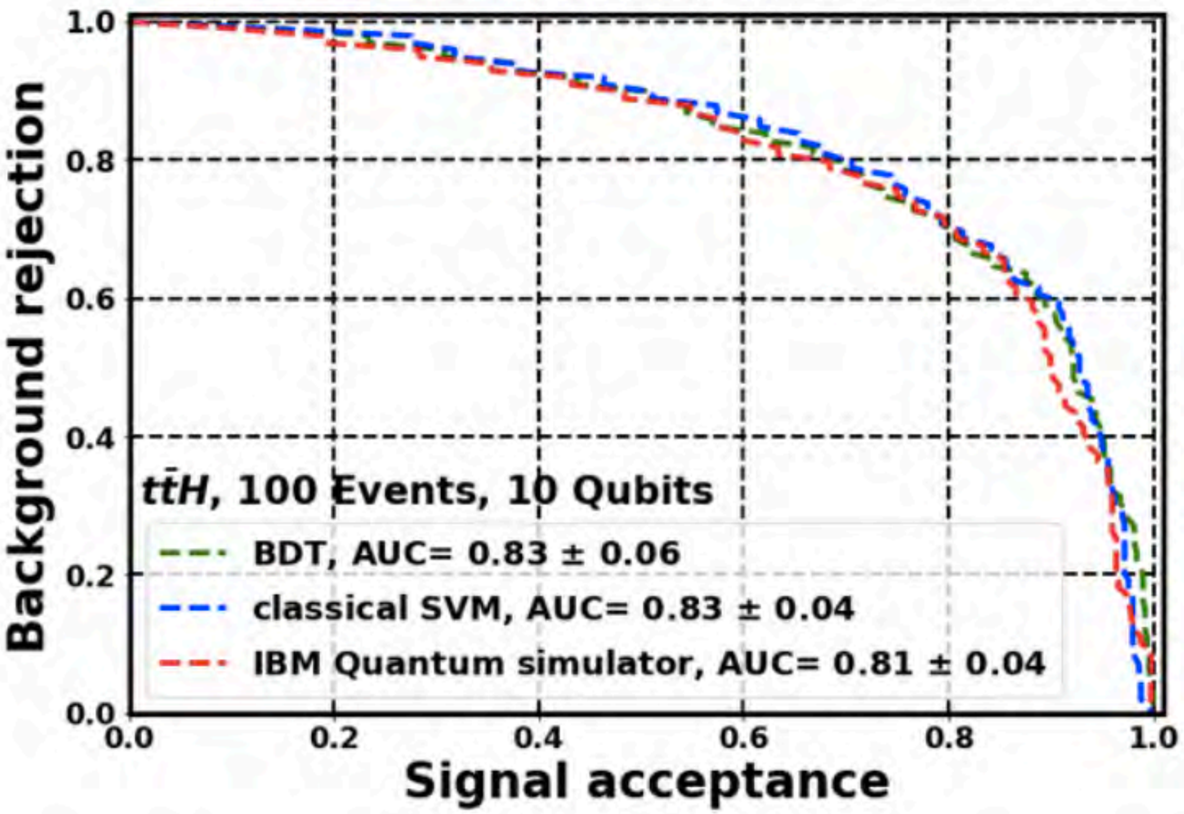
- During the training phase, a set of events are used to train the circuit W(θ) to reproduce correct classification
- Using the optimized W(θ), an independent set of events are used for evaluation and testing

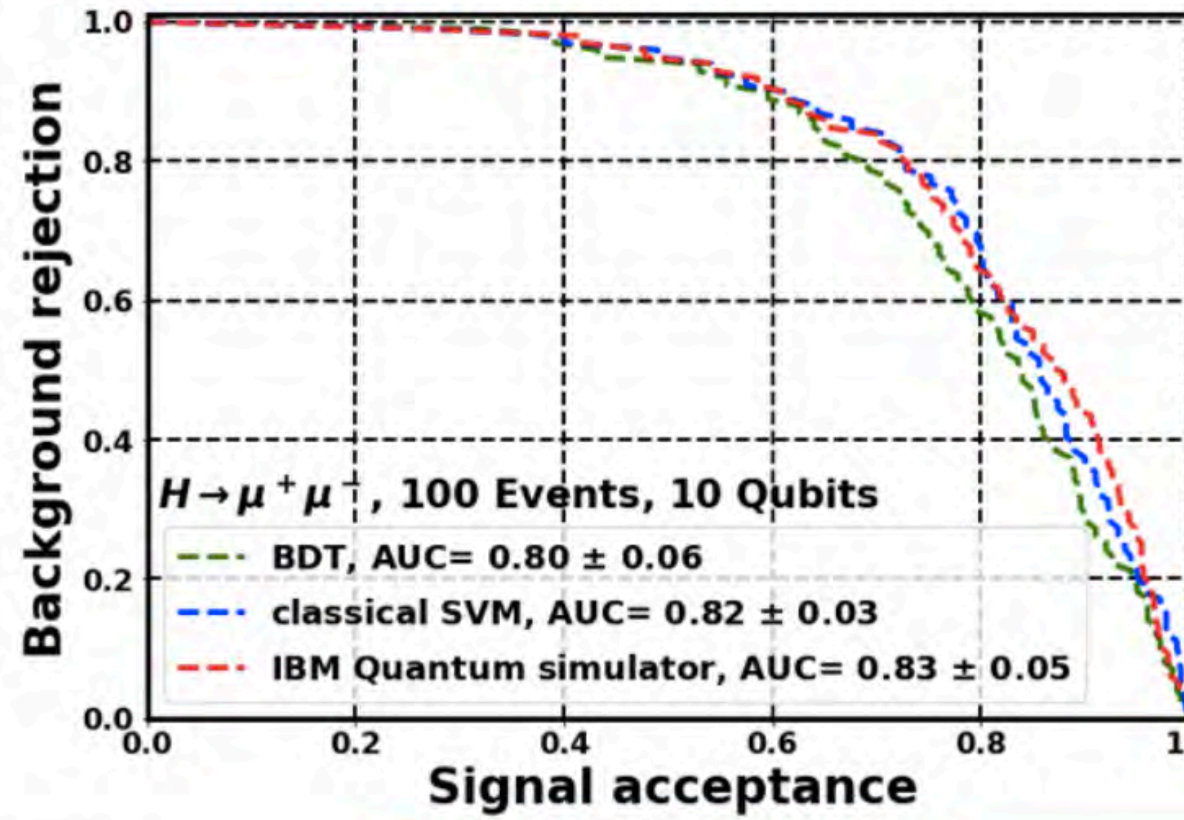
Employing Variational Quantum Classifier with quantum simulator

Using 10 qubits, we successfully finished training and testing 100 events with IBM Qiskit QASM simulator (where '100' events means 100 training events and 100 testing events).

- Here IBM Qiskit QASM quantum computer simulator is used. This simulation incorporates the hardware noise
- Quantum circuits are optimized to best fit the constraints imposed by hardware (e.g. qubit connectivity, hardware noise) and the nature of data

Employing Variational Quantum Classifier with quantum simulator





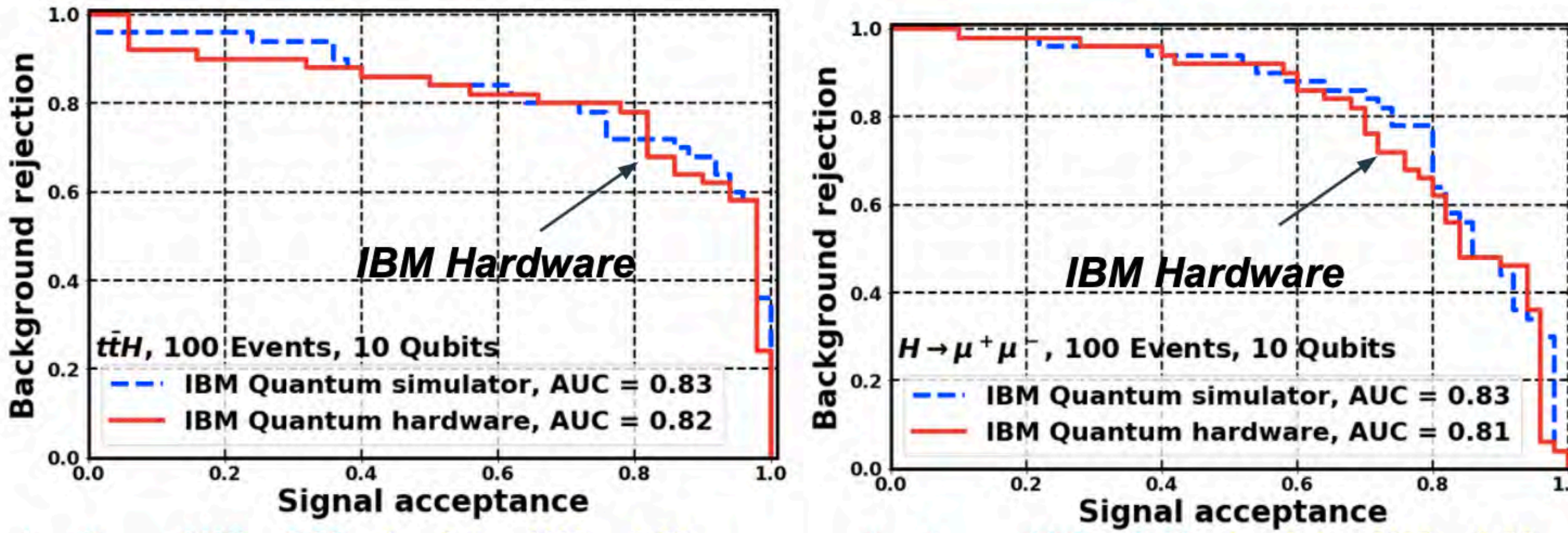
For 10 qubits, using ttH analysis dataset (100 events) and H $\rightarrow \mu\mu$ analysis dataset (100 events), Variational Quantum Classifier on IBM simulator (red) performs similarly with classical BDT (green) and classical SVM (blue).

	AUC (ttH)	AUC (H $\rightarrow \mu\mu$)
VQC	0.81	0.83
BDT	0.83	0.80
SVM	0.83	0.82

Employing Variational Quantum Classifier with quantum hardware

- With the help of IBM Research Zurich, Fermilab and BNL, we have carried out a number of jobs on the IBM superconducting quantum computers (ibmq_boeblingen, a 20-qubit machine and ibmq_paris, a 27-qubit machine). In each job, 10 qubits of the quantum computer are used to study 100 training events and 100 test events.
- For each analysis, due to current limitation of hardware access time, we apply the Variational Quantum Classifier method to one dataset on quantum hardware (rather than ten datasets on quantum simulator)

Employing Variational Quantum Classifier with quantum hardware



hardware AUC = 0.82, simulator AUC = 0.83 hardware AUC = 0.81, simulator AUC = 0.83

- **For 10 qubits, using ttH analysis dataset (100 events) and H → $\mu\mu$ analysis dataset (100 events), the result of Variational Quantum Classifier from IBM Quantum Hardware and result from Quantum Simulator are in good agreement.**
- **The hardware running time for 100 events is 200 hours**

Example 2: Employing Quantum Support Vector Machine (QSVM) Kernel for ttH analysis

<u>Phys. Rev. Research 3, 033221 (2021)</u>

Quantum SVM Kernel method

- ***Quantum SVM Kernel method*** ***(introduced by IBM, published in Nature 567 (2019) 209):***
  - ***map classical data $\vec{x}$ to a quantum state $|\Phi(\vec{x})\rangle$ using a Quantum Feature Map function;***
  - ***calculate the similarity between any two data events ("kernel entry") as $K(\vec{x}_1,\vec{x}_2)=|\langle\Phi(\vec{x}_1)|\Phi(\vec{x}_2)\rangle|^2$ using a quantum computer;***
  - ***then using the kernel entries to find a separating hyperplane that separates signal from background.***

map classical data

$\vec{x}_1 \rightarrow |\Phi(\vec{x}_1)\rangle$

$\vec{x}_2 \rightarrow |\Phi(\vec{x}_2)\rangle$

$\vec{x}_3 \rightarrow |\Phi(\vec{x}_3)\rangle$

...

calculate kernel entries

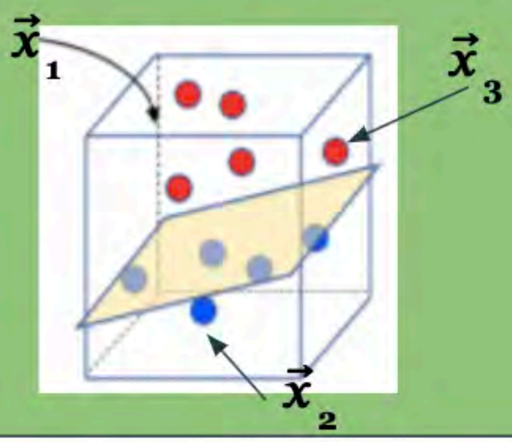
$K(\vec{x}_1,\vec{x}_2)=|\langle\Phi(\vec{x}_1)|\Phi(\vec{x}_2)\rangle|^2$

$K(\vec{x}_1,\vec{x}_3)=|\langle\Phi(\vec{x}_1)|\Phi(\vec{x}_3)\rangle|^2$

$K(\vec{x}_2,\vec{x}_3)=|\langle\Phi(\vec{x}_2)|\Phi(\vec{x}_3)\rangle|^2$

...

find separating hyperplane



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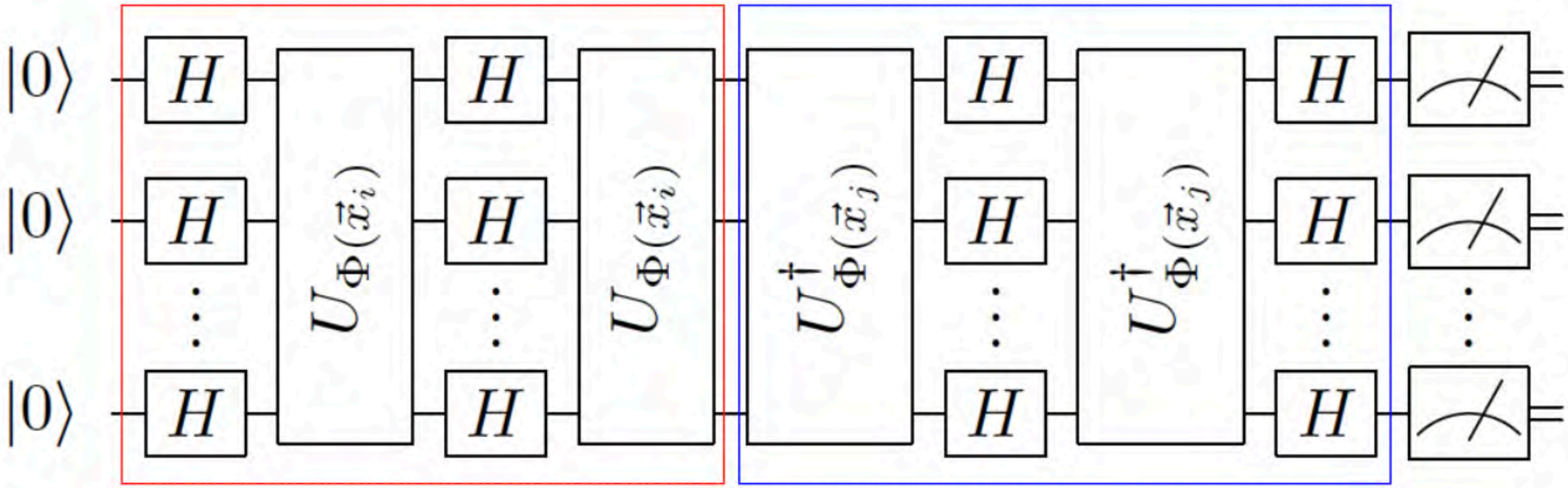
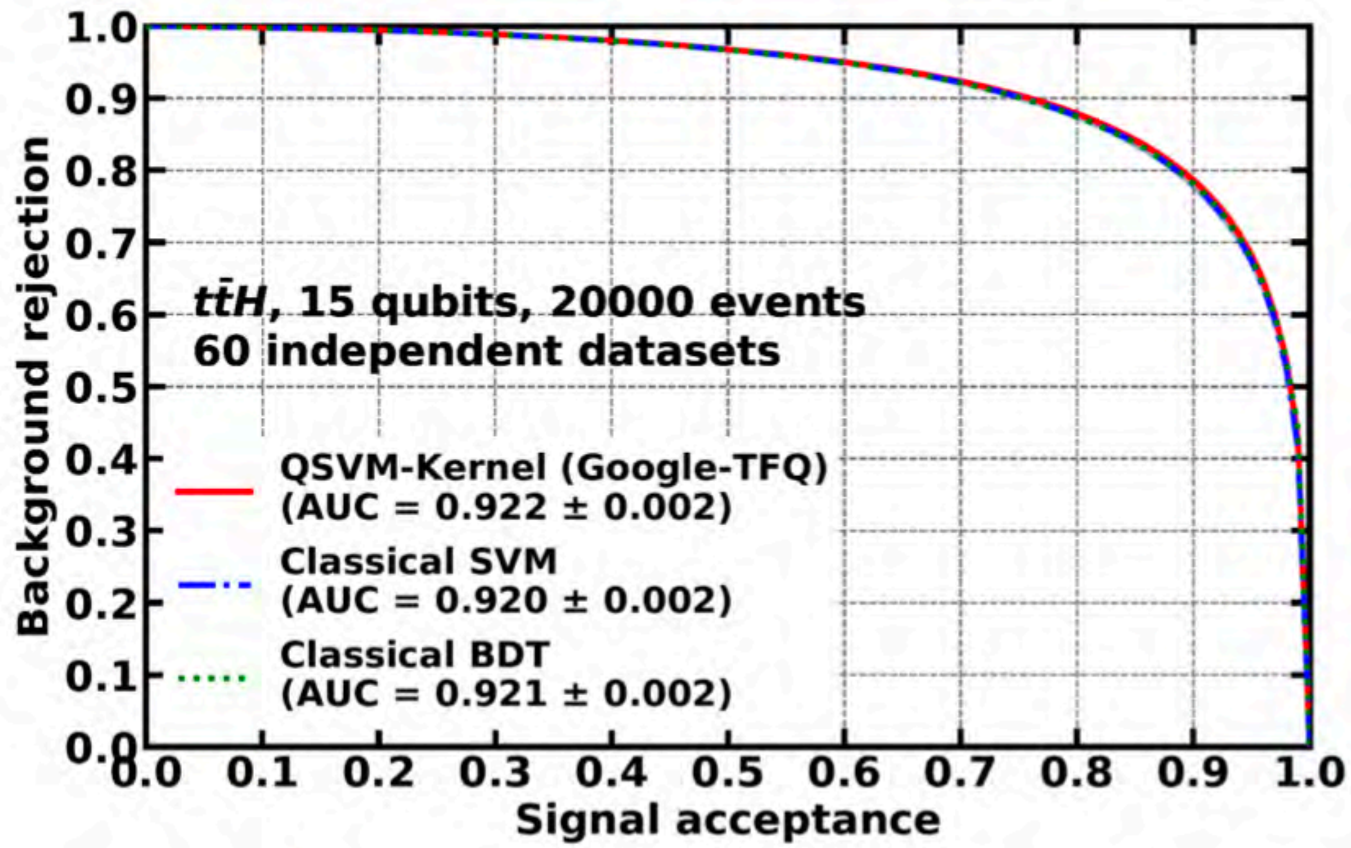


Employing Quantum SVM Kernel method with quantum simulator

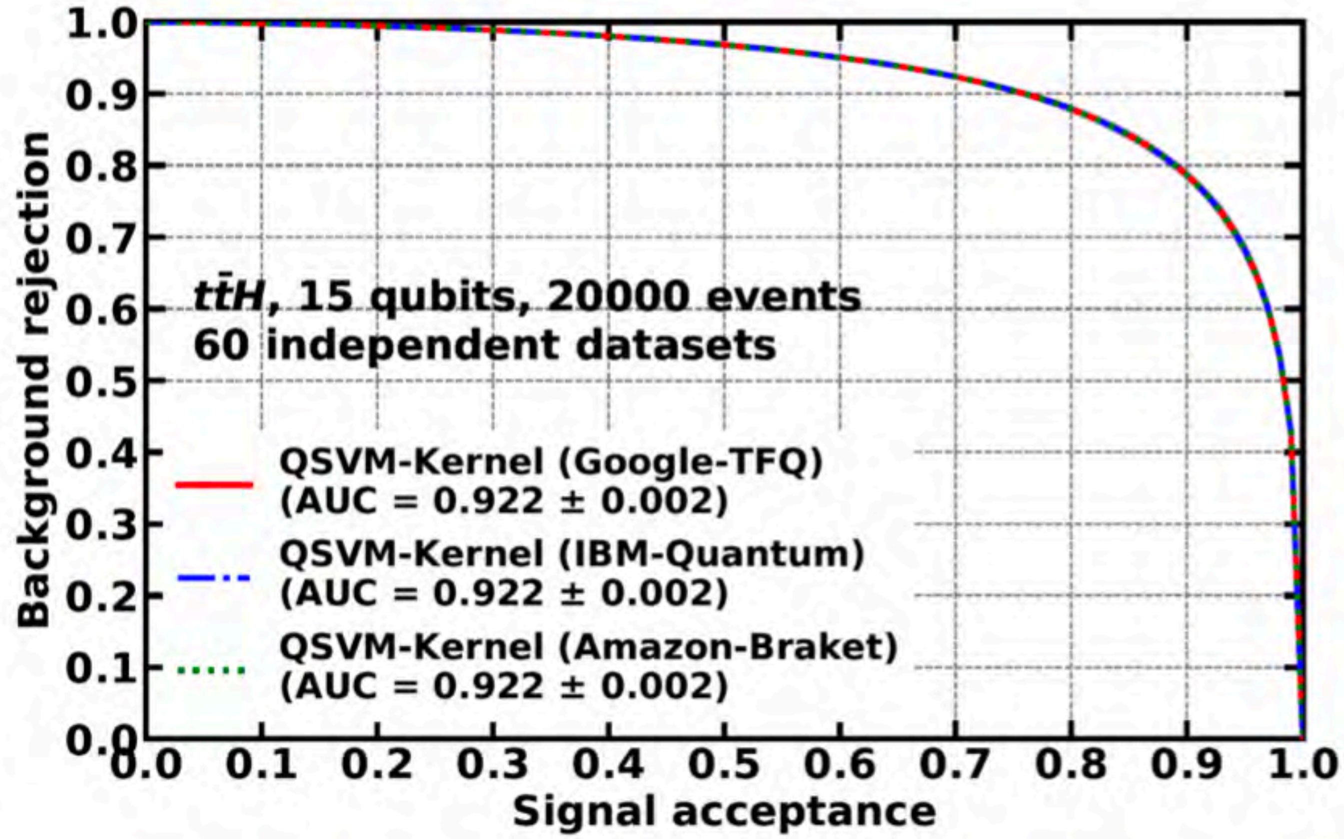
- ***We have implemented the QSVM Kernel algorithm using the qsim Simulator from the Google TensorFlow Quantum framework, the Statevector Simulator from the IBM Qiskit framework and the Local Simulator from the Amazon Braket framework***
    - ***These simulators represent the ideal quantum hardware that performs infinite measurement shots and experiences no hardware device noise***
    - ***We have overcome the challenges of heavy computing resources in the use of up to 20 qubits and up to 50000 events on the quantum computer simulators***

Employing Quantum SVM Kernel method with quantum simulator



- For 15 qubits, using ttH analysis dataset (20000 events), QSVM Kernel on simulator (red) achieves similar performances with classical SVM (blue) and classical BDT (green).

Employing Quantum SVM Kernel method with quantum simulator

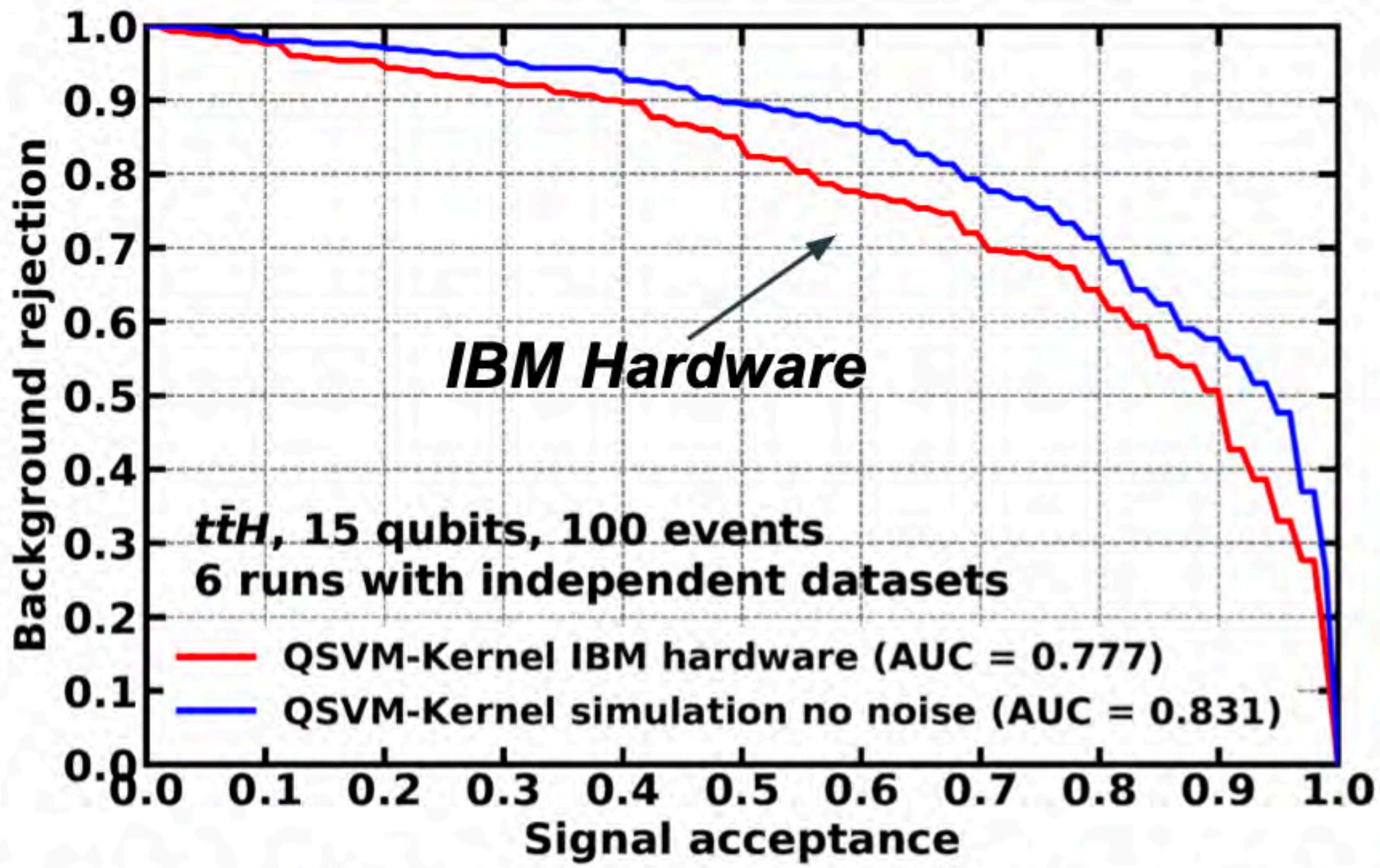


- For 15 qubits, using ttH analysis dataset (20000 events), Google qsim simulator (red), IBM statevector simulator (blue), and Amazon local simulator (green) provide identical performances for QSVM Kernel method

Employing Quantum SVM Kernel method with quantum hardware

- ***We have also been running the QSVM Kernel algorithm on quantum computer hardware provided by IBM (based on superconducting circuits)***
  - *to assess the quantum machine learning performances on today's noisy quantum computer hardware*
  - *due to current limitation of access time on imbq_paris, we only process six datasets of 100 training events and 100 test events*

Employing Quantum SVM Kernel method with quantum hardware



hardware AUC = 0.777

simulator AUC = 0.831

- Using ttH analysis dataset (100 events), the QSVM Kernel results on the IBM Quantum Hardware (15 qubits) are promising and approaching the QSVM Kernel results on Quantum Simulator (the difference is likely due to effect of hardware noise)
- ***The average hardware running time is approximately 680 minutes per run***

Quantum machine learning for HEP

- The results (on both simulators and hardware) demonstrate quantum machine learning on the gate-model quantum computers has the ability to differentiate signal and background in realistic physics datasets

- Future developments:
  - Will investigate further and hopefully will see soon quantum machine learning outperforms classical machine learning, in particular, when more qubits and better algorithms are utilized
  - Will make use of quantum computers made in China (e.g. 本源). Future quantum computers might offer speed ups in quantum machine learning which could be critical for the HEP community

Quantum machine learning for HEP: challenges

- Difficulties at present:
  - Only ~100 events are used in hardware jobs
    - Limited access time and long execution time
  - Only ~10 qubits are used in hardware jobs
    - Limited by the hardware noise

- To use Quantum Computer Hardware for Machine Learning in High-Luminosity LHC and future collider physics analyses, we need to extend our studies to larger event sample sizes and more qubits

Quantum machine learning for HEP: opportunities

- **Quantum computing industry expect that quantum hardware in the future will reduce noise, increase number of qubits and speed up running time.**

- **With the large investments in quantum computing and fierce international competitions in technology, this expectation is realistic.**

- **The HEP community should be well prepared to make use of potential quantum advantage in our data challenge.**

- **Conversely, applications in HEP could contribute to developments of quantum technologies.**

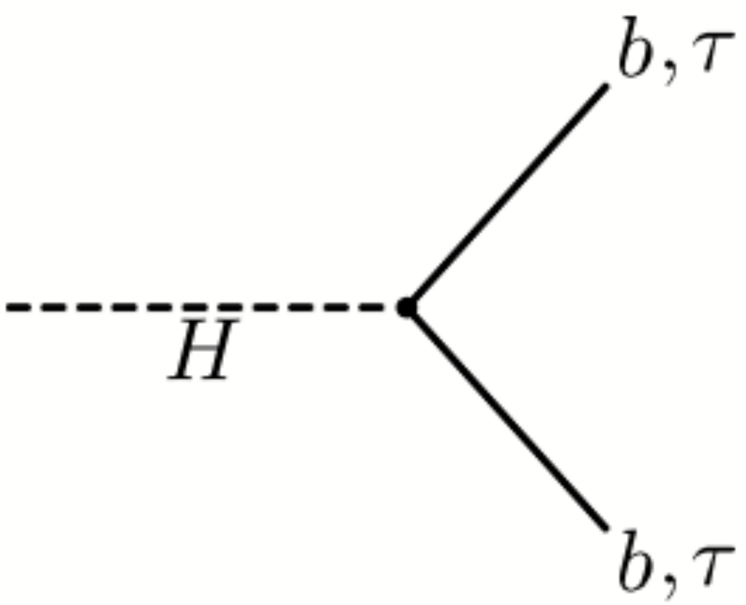
Summary

- I have been working on LHC physics analyses, detector upgrades and quantum machine learning applications
- ATLAS and CMS keep improving sensitivity for **Higgs property measurements** (including Higgs couplings to fermions and self-couplings)
  - Using the Higgs boson as a tool to search for **new physics**
- **Machine learning** greatly enhances our capability to identify rare signal in immense background
  - **Quantum machine learning** could possibly become another powerful tool for high energy physics
- If you are interested in a related research topic and/or a postdoc/PhD position, don't hesitate to contact me via email (czhouphy@pku.edu.cn)

Thank you!

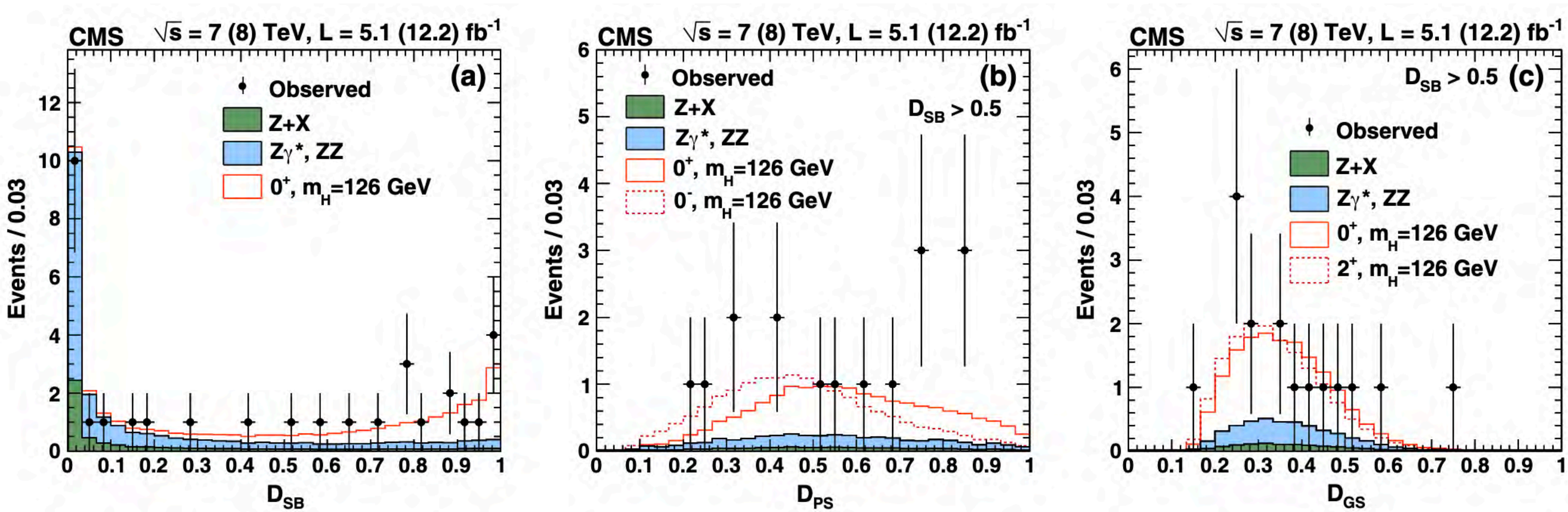
Higgs couplings to τ leptons & to b quarks

- H→$\tau\tau$ is currently the only established leptonic decay mode of the Higgs boson
  - The first observation of the H→$\tau\tau$ decay mode with **5.5σ** was achieved from a combination of ATLAS and CMS Run 1 results
- H→$b\bar{b}$ decay mode has largest branch ratio (~58%) and was established in 2018 using Run 1+Run 2 data:
  - ATLAS observed a H→$b\bar{b}$ signal with **5.4σ**
  - CMS observed a H→$b\bar{b}$ signal with **5.6σ**



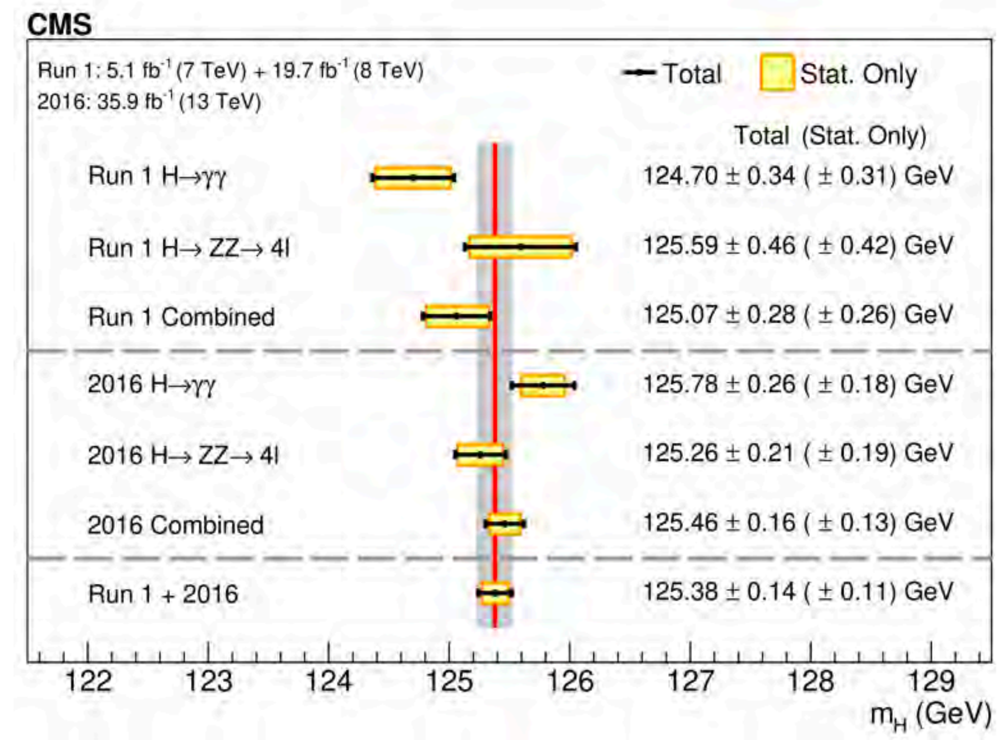
Higgs spin and CP

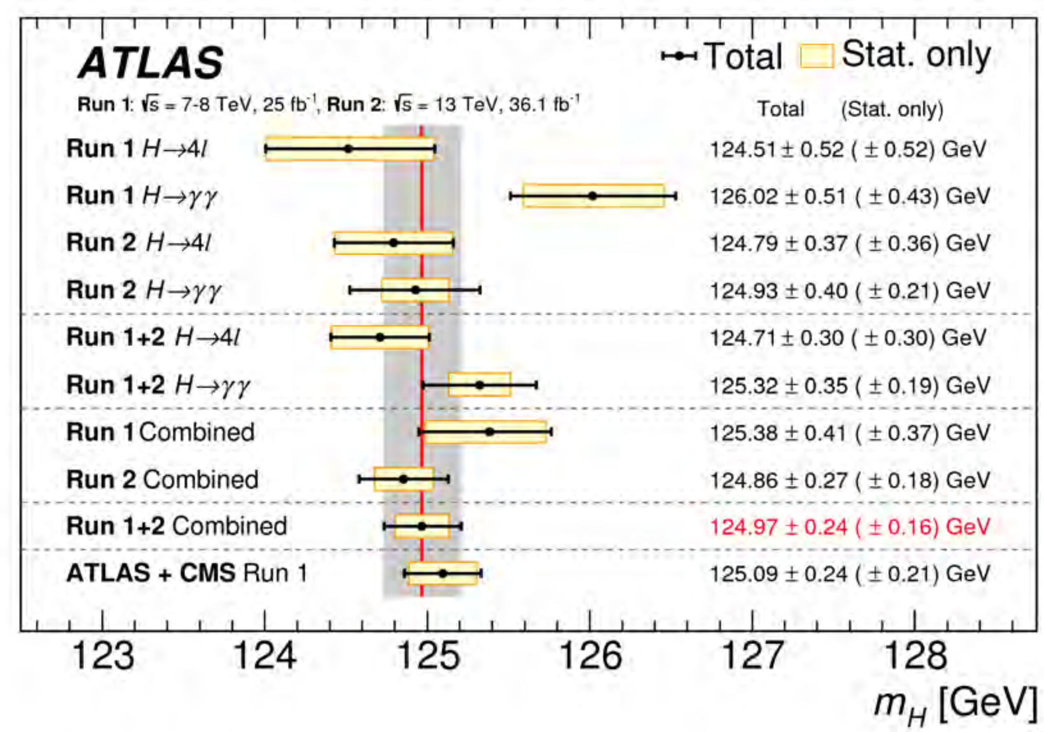
- The SM Higgs boson is a scalar: spin-zero, CP-even
- **The observed boson was verified to be spin-zero in Run 1**
- Non-CP-even couplings of the Higgs boson were searched using ggF+2j, VBF, VH and ttH productions and H→ZZ, H→WW and H→$\tau\tau$ decays.
  - **Data disfavor the pure CP-odd scenario, stringent constraints on CP mixing are given**



Higgs mass

- Higgs mass is the only free parameter in the SM Higgs sector
- Measured in channels with best resolution: H→ZZ*→4l and H→γγ
  - Rely on energy/momentum calibration
- ATLAS+CMS Run 1: 125.09 ± 0.24 GeV
  - 0.19% uncertainty
- CMS Run 1+partial Run 2: 125.38 ± 0.14 GeV
  - 0.11% uncertainty
- ATLAS Run 1+partial Run 2: 124.97 ± 0.24 GeV
  - 0.19% uncertainty
- Precision not a limiting factor for other Higgs measurements

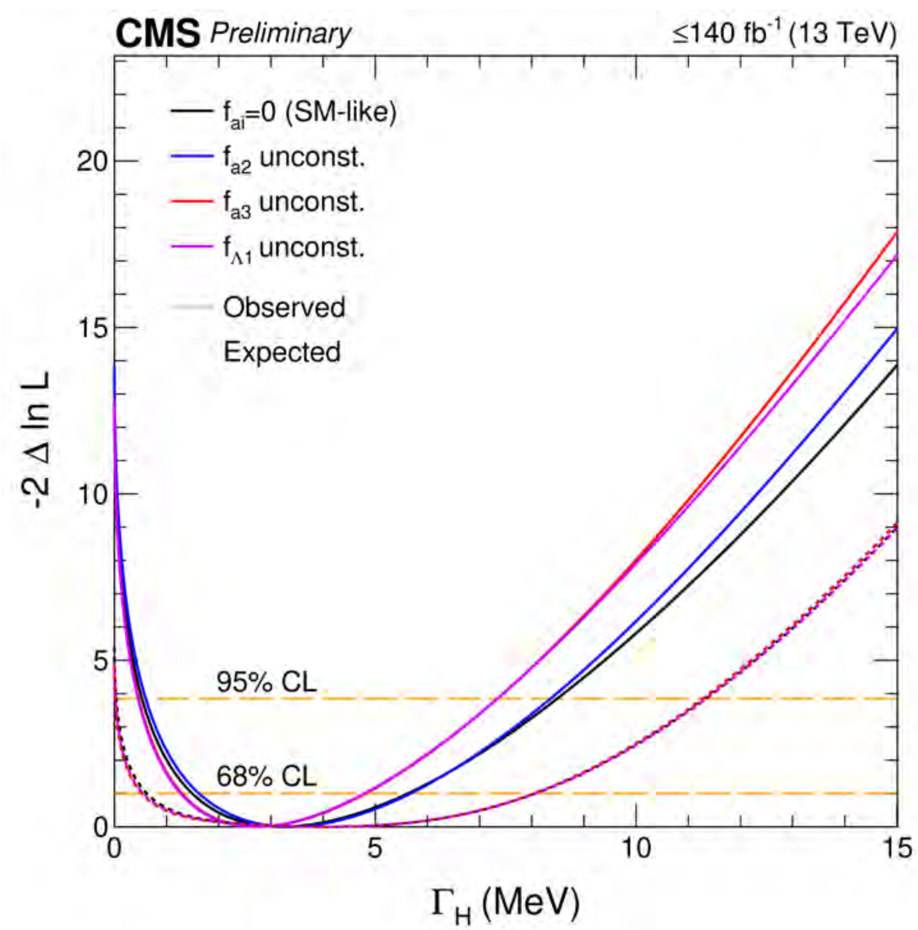




Higgs width

- SM prediction of Higgs width: 4.1 MeV
  - direct measurement limited by detector resolution
- Constrain Higgs width by comparing on-shell and off-shell Higgs rates using H→ZZ*→4l and H→ZZ*→2l2v
  - Higgs width is determined to be $3.2^{+2.4}_{-1.7}$ MeV
- In H→γγ, interference between Higgs signal and continuous background can cause Higgs mass shift, which depends on Higgs width
  - this effect can also constrain Higgs width

$$\Gamma_H = \frac{\mu_{off\ shell}}{\mu_{on\ shell}} \times \Gamma_H^{SM} \qquad (\kappa_t^2\kappa_V^2)_{on\ shell} = (\kappa_t^2\kappa_V^2)_{off\ shell}$$



- I did not directly work on spin/CP/mass/width analyses, but oversaw several such analyses as the ATLAS Higgs-Gamma convener